# Expect the Unexpected!

Ultra High Energy cosmic rays!

Dark matter!

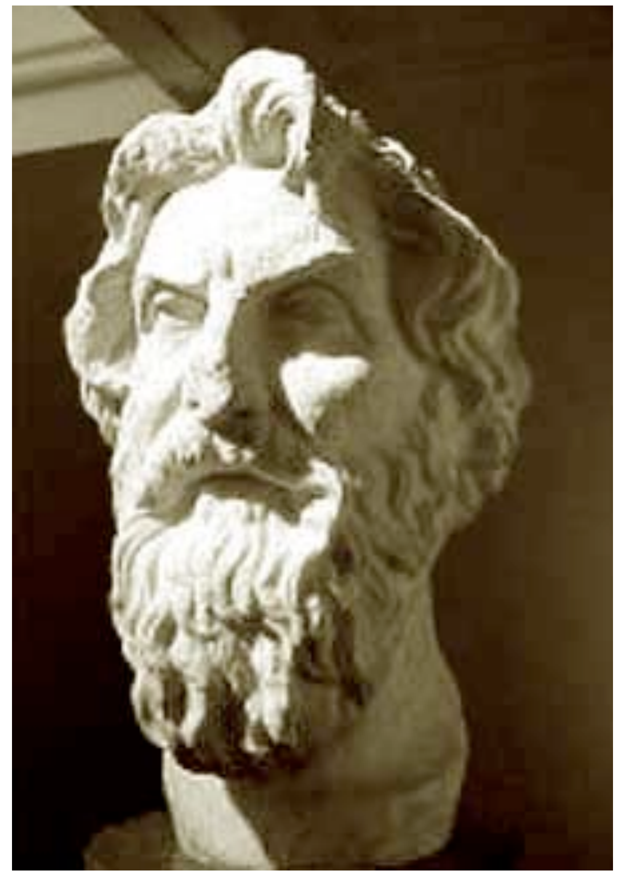
Dark Energy!

# Aristarchus of Samos

- Aristarchus lived on the Greek island of Samos from 310 BC to 230 BC.


- Aristarchus postulated that the planets orbited the Sun, not the Earth, over a thousand years before Copernicus and Galileo made similar arguments.

- Aristarchus' discoveries were too unexpected for most people to accept at that time.

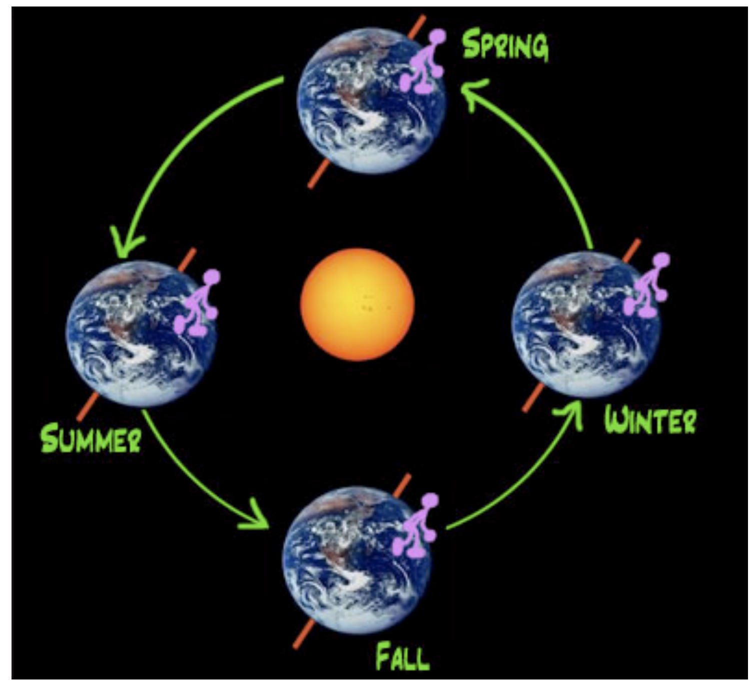


Aristarchus of Samos

We've learned that we are on a wilder ride than that at any amusement park!

# The Earth spins on its axis…

…*while* it orbits the Sun, like a crazy Tilt-a-Whirl!

# The Sun orbits the center of the Milky Way

- The Sun has orbited the center of the Milky Way Galaxy more than 20 times during its 5 billion year lifetime!


And the Milky Way is only one of an estimated 50 billion galaxies…

*Hubble Deep Field in the Northern sky, in the direction of Ursa Major*

…which are all moving away from each other!

*Hubble Deep Field in the Northern sky, in the direction of Ursa Major*

## …which are all moving away from each other!

*Hubble Deep Field in the Northern sky, in the direction of Ursa Major*

## …which are all moving away from each other!

*Hubble Deep Field in the Northern sky, in the direction of Ursa Major*

Edwin Hubble discovered all galaxies are moving away from each other.

Until 1998,
most astronomers assumed that gravity will take over, and the rate at which galaxies are moving away from each other would slow down.

However, in 1998 it was learned that the
Universe will expand forever, and faster and faster!

We’ve learned that we are on a ride wilder than any carnival ride.

And the ride is not going to stop and it’s not slowing down!

What keeps the ride going?

Dark Energy.

# Fermilab Center for Particle Astrophysics

- Cosmic Microwave Background
  - R&D: QUIET (Q/U Imaging ExperimenT)
- Physics at high energy scales
  - Pierre Auger Observatory
  - GammeV
- Dark matter
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe
- Dark energy
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

# What was unexpected?

- Cosmic Microwave Background — Unexpected noise
  - R&D: QUIET (Q/U Imaging ExperimenT)
- Physics at high energy scales — Unexpected transparency
  - Pierre Auger Observatory
  - GammeV
- Dark matter — Unexpected flat rotation curves
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe
- Dark energy — Unexpected accelerated expansion
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

# Cosmic Microwave Background

# What was unexpected?

- Cosmic Microwave Background — Unexpected noise
  - R&D: QUIET (Q/U Imaging ExperimenT)
- Physics at high energy scales — Unexpected transparency
  - Pierre Auger Observatory
  - GammeV
- Dark matter — Unexpected flat rotation curves
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe
- Dark energy — Unexpected accelerated expansion
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

# Cosmic microwave background

- If there was a Big Bang, the universe immediately following would have been very hot, $>10^{12}$ K, corresponding to short, gamma ray wavelengths.

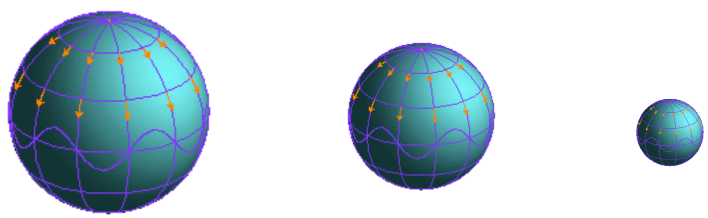
# Cosmic microwave background

- As the universe expanded, the cosmological redshift would stretch the short wavelength radiation into longer, millimeter waves (1.1 mm).

- We call this radiation the cosmic microwave background (CMB).

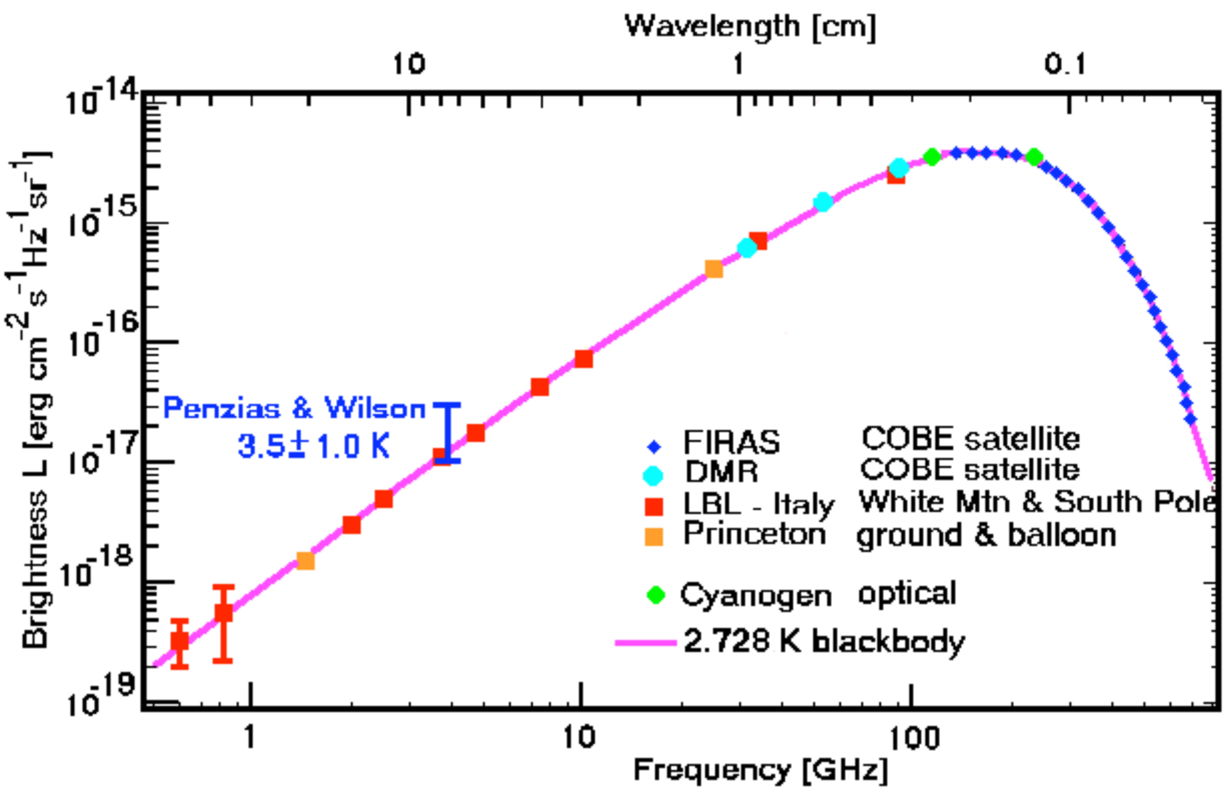
# Cosmic microwave background

- If these pictures are run backwards in time, the wavelength of light becomes shorter and shorter and matter becomes denser and denser, implying that the universe began in a hot dense state.



# Cosmic microwave background

- So, detection of cosmic microwave background radiation would be evidence for a Big Bang.

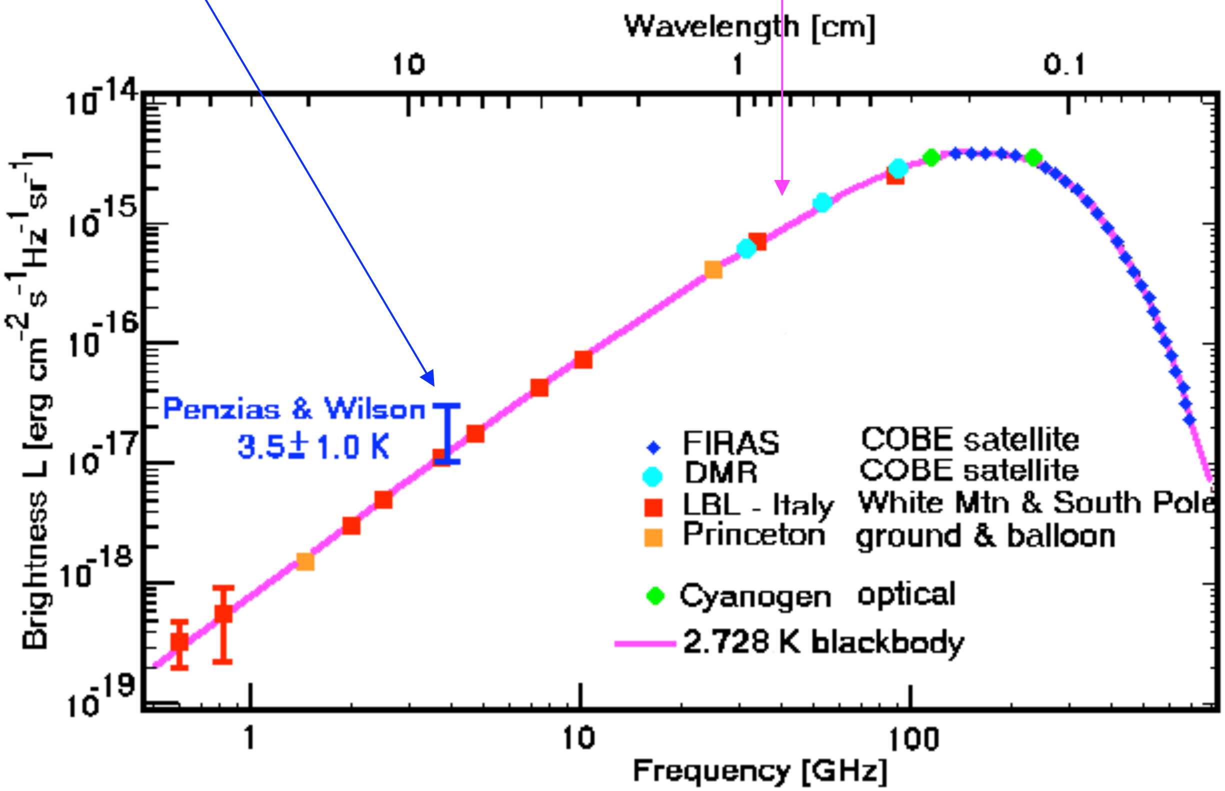


# Cosmic microwave background

- Penzias and Wilson, working on a communications antenna.
- They detected a faint background noise in all directions.
- All efforts to eliminate this noise, even removal of static noise-generating pigeon droppings from their antenna, failed to eliminate the noise.
- Hearing about the then-theoretical CMB, they announced their findings.

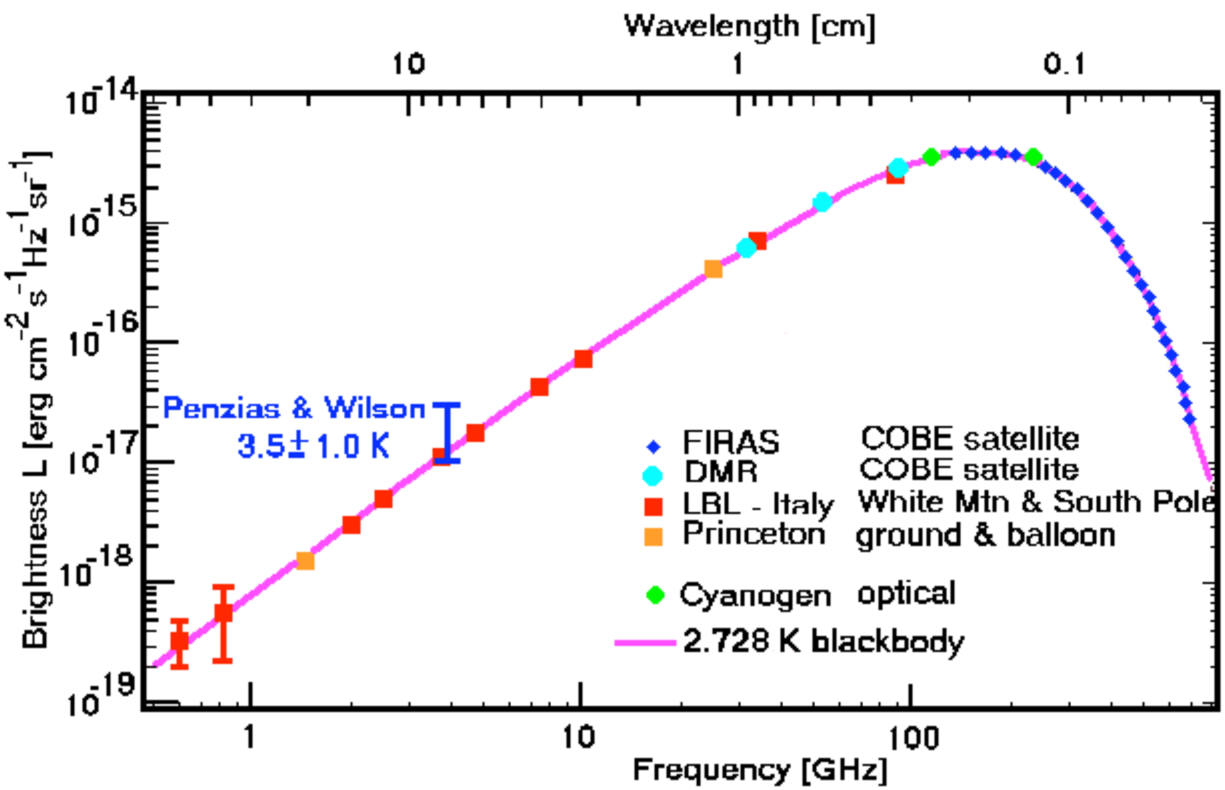
# Cosmic microwave background

- Their data point (and many since then) fit the curve for a 2.728 K black body!



# Cosmic microwave background

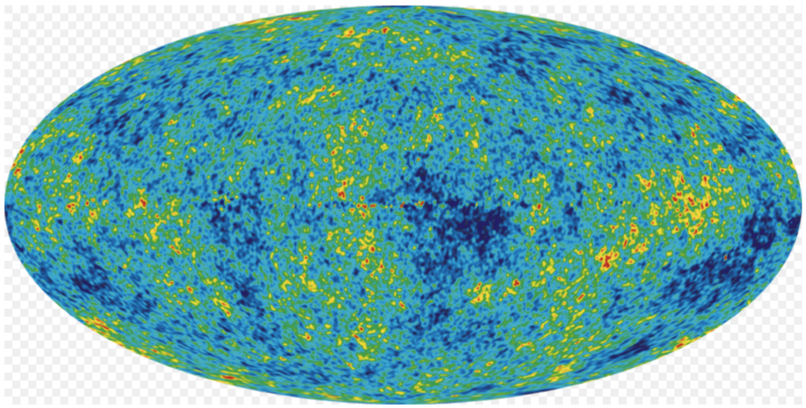
- Detection of the cosmic microwave background is a principal reason why the Big Bang is accepted by astronomers as the correct cosmological theory.



# QUIET

- The intensity anisotropy pattern of the Cosmic Microwave background radiation has already been measured to an extraordinary precision

- The polarization anisotropies of the CMB are an order of magnitude smaller than the intensity anisotropies and provide additional keys to understanding cosmology.



# QUIET

- QUIET hopes to measure the tiny polarization of the CMB which can reveal information about the early universe.

- Of special importance and interest are the B-modes expected from gravitational waves in the inflationary epoch, since a detection would allow unique access to the very first moments of the Universe.

QUIET telescope in Chajnantor Plateau, Atacama, Chile

# Physics at High Energy Scales

# What was unexpected?

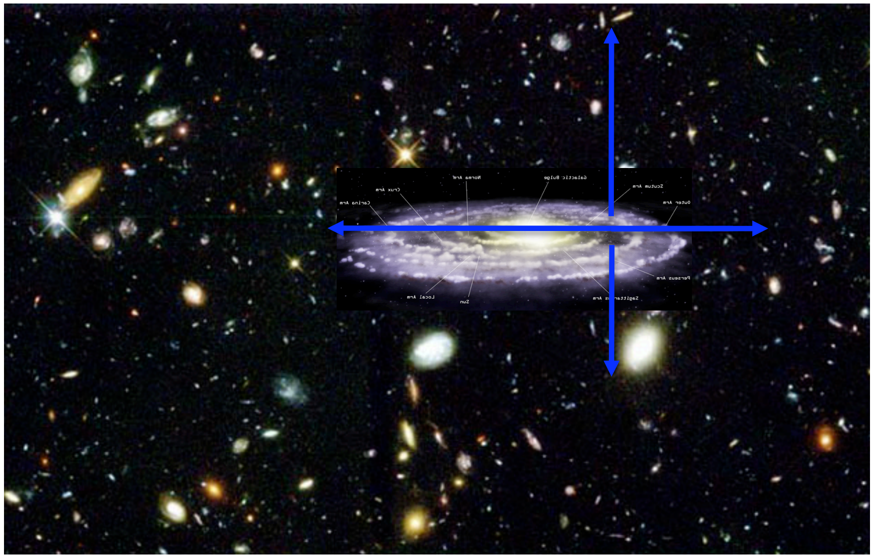
- Cosmic Microwave Background — Unexpected noise
  - R&D: QUIET (Q/U Imaging ExperimenT)
- Physics at high energy scales — Unexpected transparency
  - Pierre Auger Observatory
  - GammeV
- Dark matter — Unexpected flat rotation curves
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe
- Dark energy — Unexpected accelerated expansion
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

# Transparency

- Photons and particles from Galactic sources must travel through our Galaxy to get to us.

- Extra-Galactic photons and particles must travel through intergalactic space (and our Galaxy) to get to us.

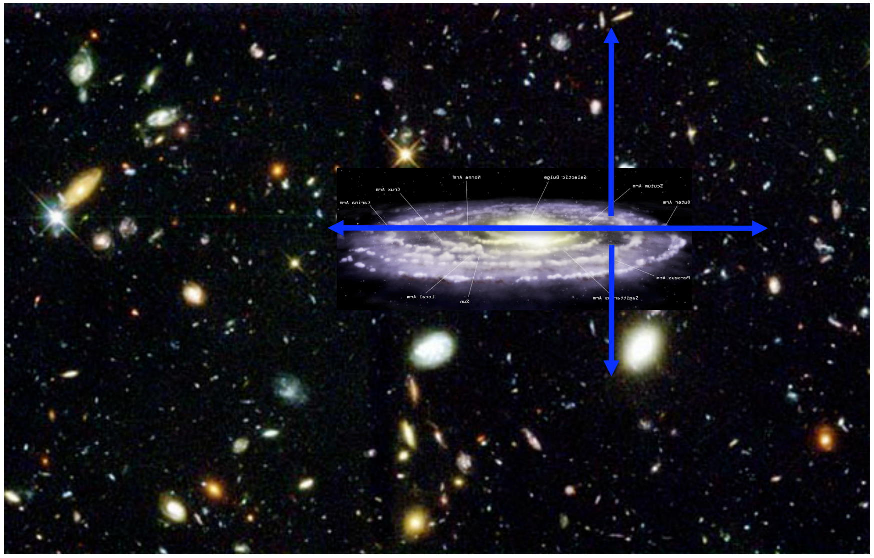
- A lot can happen along the way.



# Transparency

- If the particles and photons can travel to us unimpeded, we say the intervening matter is transparent to the particles and photons.

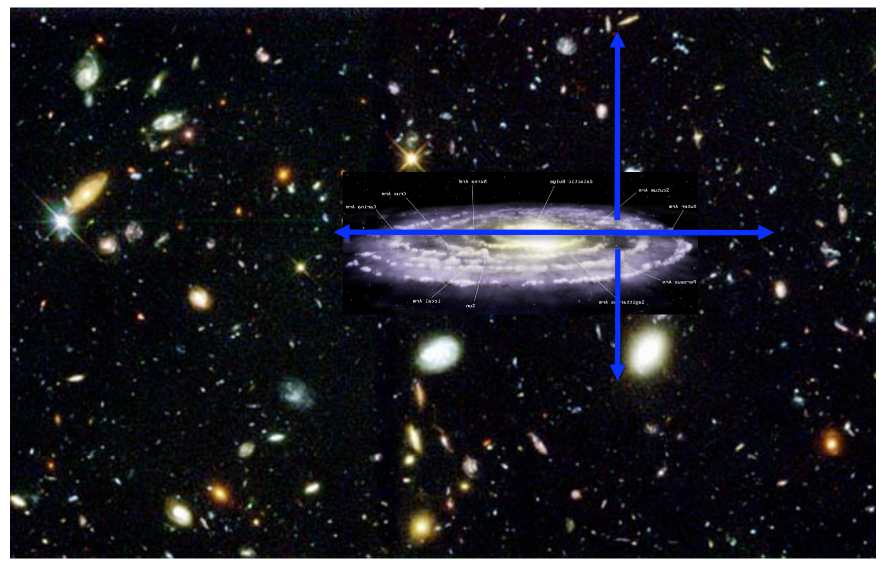
- There is some chance that the photons and particles will interact with the intervening matter before they reach us, meaning the intervening matter is not transparent.



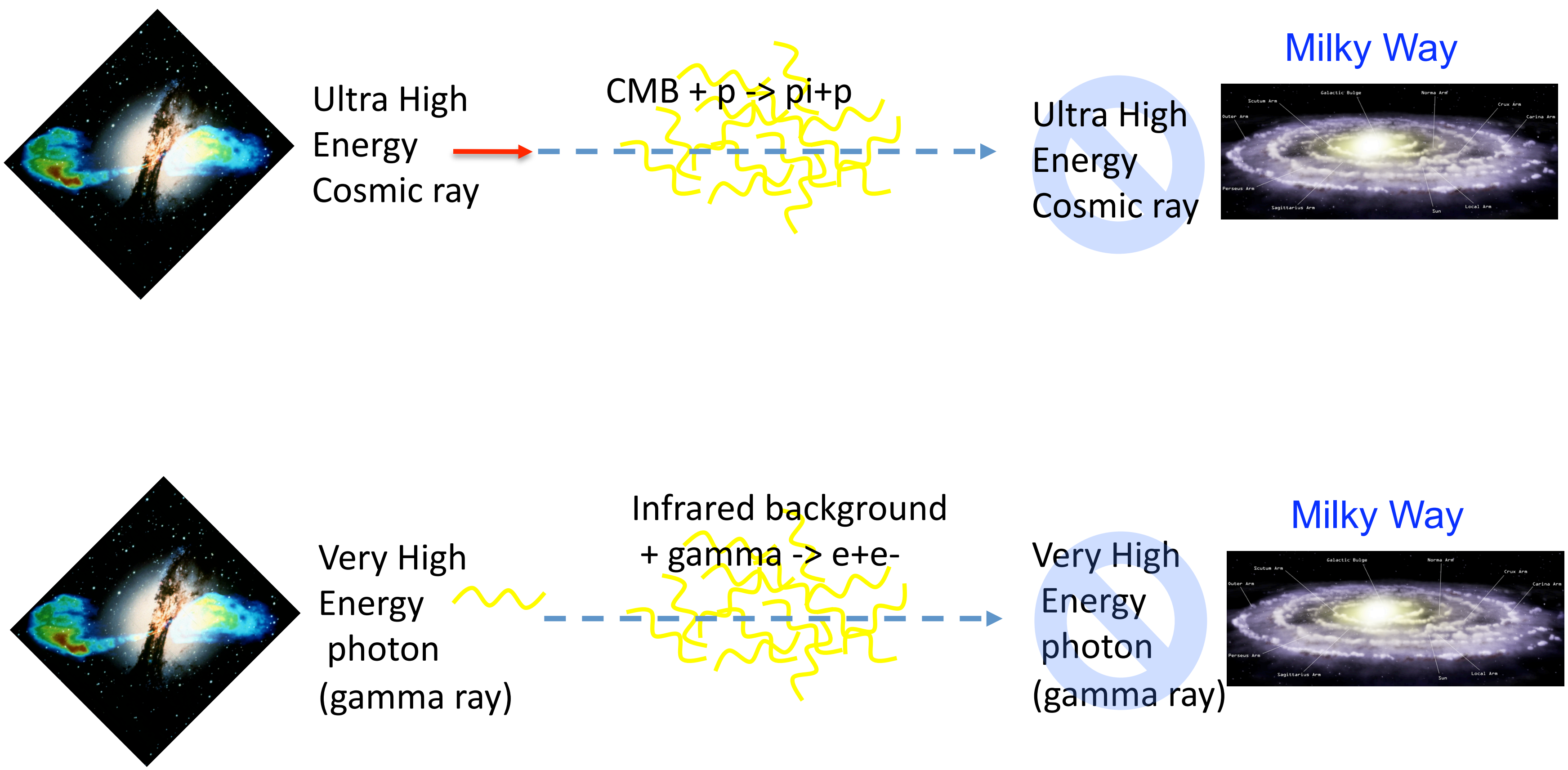
# Transparency

- Using our current understanding of physics and the universe, we can predict which particles and photons of certain energies will interact before reaching us and which we expect to travel to us unimpeded.

- *If we see the unexpected, perhaps we have learned something new!*



# Non-transparent



# Calculation of the required UHECR proton energy for pion photoproduction

- The approach is to calculate the proton energy, $E_p$, required for pion photoproduction using conservation of 4-momenta, *P*.
- Considering the left hand side in the lab frame and the right hand side in the center-of-mass frame, where
  - $E_p$ = UHECR proton energy (the unknown)
  - *Eg* = average CMB photon energy = 6.34x10-4 eV [4]
  - $m_p$ = 938.27 MeV/c2
  - $m_{p0}$ = 134.97 MeV/c2
  - *P* = 4-momentum
- Conclusion: $E_p$~2x10[20] eV

$$\gamma + p \rightarrow p\pi^0$$

$$\text{Lab} \rightarrow \text{Center of mass}$$

$$(P_{p\mu} + P_{\gamma\mu})^2 = P_{TOT\mu}P^{\mu}_{TOT}$$

$$P_{p\mu}P^{\mu}_{p} + 2P_{p\mu}P^{\mu}_{\gamma} + P_{\gamma\mu}P^{\mu}_{\gamma} = P_{TOT\mu}P^{\mu}_{TOT}$$

$$(m_p c^2)^2 + (2E_p E_\gamma) + (m_\gamma c^2)^2 = \left((m_p + m_{\pi^0})c^2\right)^2$$

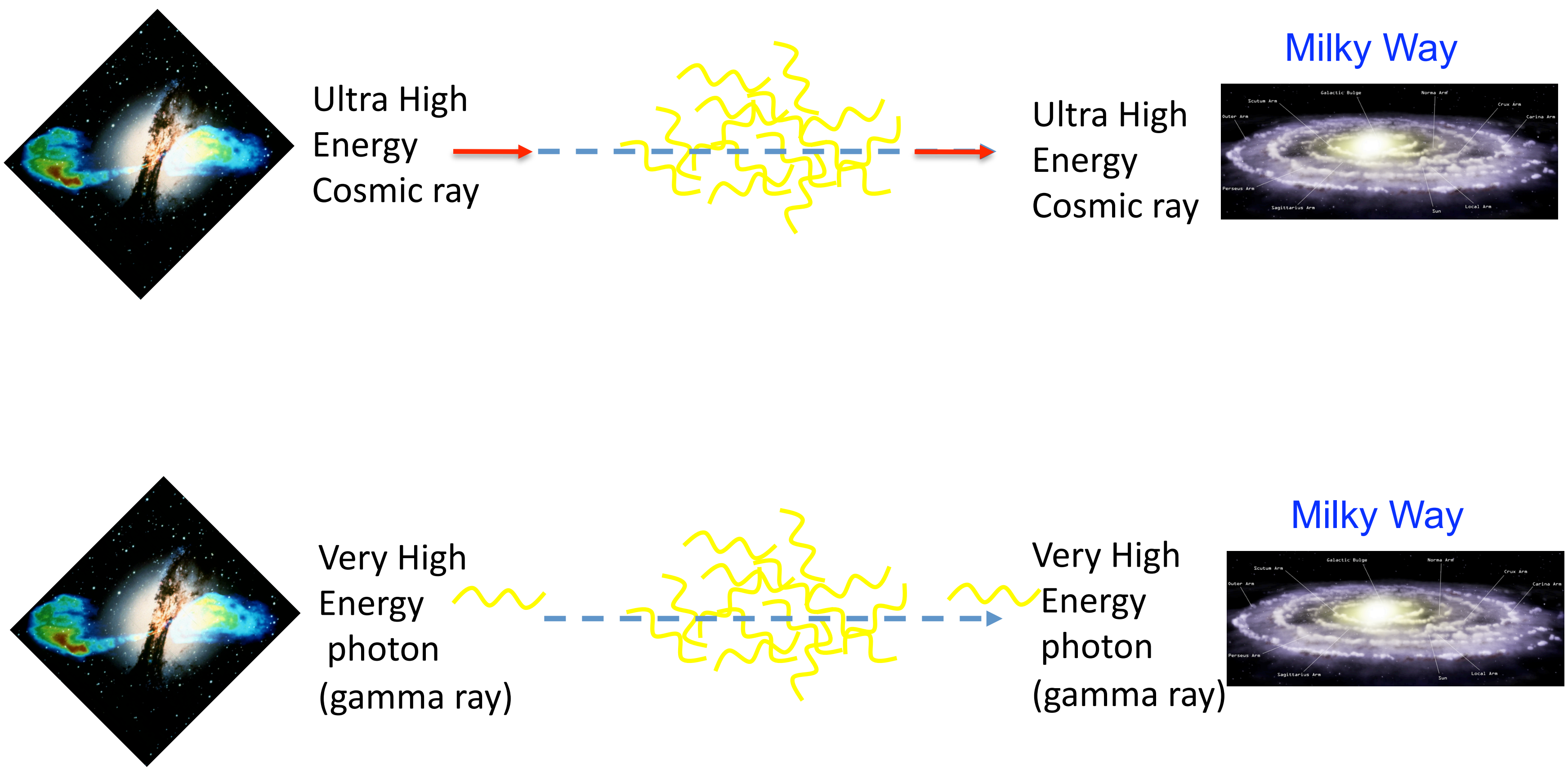
$$m_\gamma c^2 = 0, \text{because it's a photon}$$

$$E_p = \frac{m_{\pi^0}}{2E_\gamma}(2m_p + m_{\pi^0})$$

$$E_p = \frac{(134.97 MeV/c^2)c^2}{2(6.34x10^{-4} eV)}\left(\frac{(2*938.27 MeV) + 134.97 MeV)}{c^2}c^2\right)$$

$$E_p \approx 2x10^{20} eV$$

# Unexpected transparency



Pierre Auger Observatory

# GZK (Greisen-Zatsepin-Kuzmin) effect

- The CMB has a blackbody spectrum with T=2.7 K corresponding to mean energy of $6.34 \times 10^{-4}$ eV.

- A proton of high enough energy(> $7 \times 10^{19}$ eV) will interact inelastically with CMB photons producing pions via

$$\gamma + p \rightarrow n\pi^{+}$$

$$\gamma + p \rightarrow p\pi^{0}$$

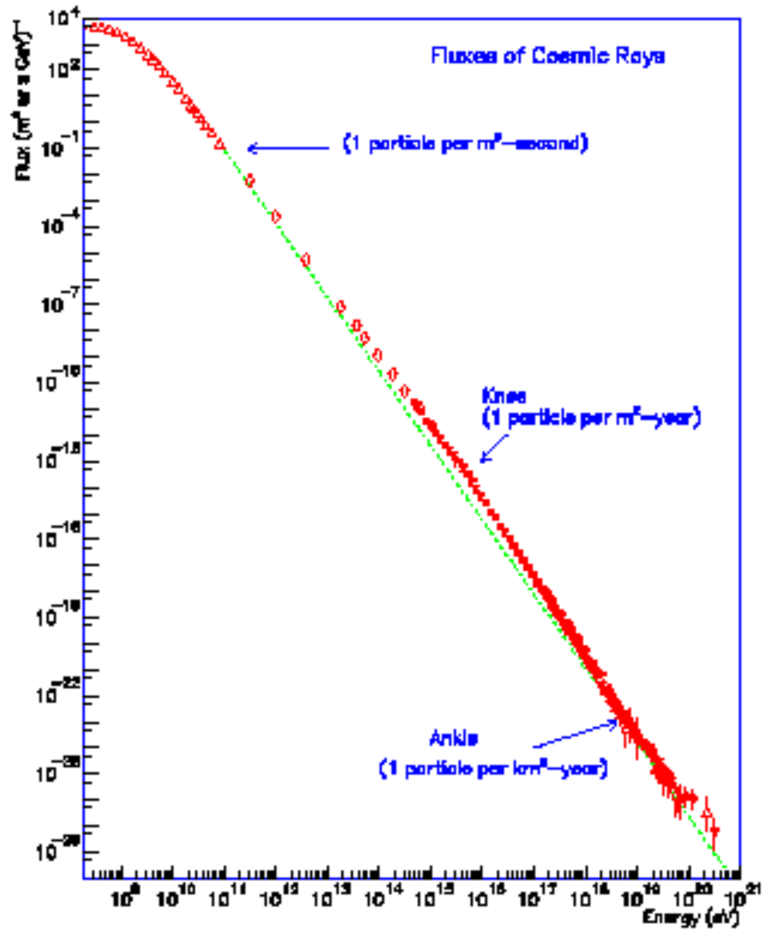
# GZK cutoff

- With each collision, the proton would lose roughly 20% of its energy
- This only happens for cosmic rays that have at least 6 x $10^{19}$ eV of energy, and this is the predicted GZK cutoff.
- So if cosmic rays were given an initial energy greater than that, they would lose energy in repeated collisions with the cosmic microwave background until their energy fell below this cutoff.
- However, if the source of the cosmic ray is close enough, then it will not have made very many collisions with microwave photons, and its energy could be greater than the GZK cutoff.
- This distance is about 150 million light years.   (~40Mpc)

# Unexpected transparency to CMB

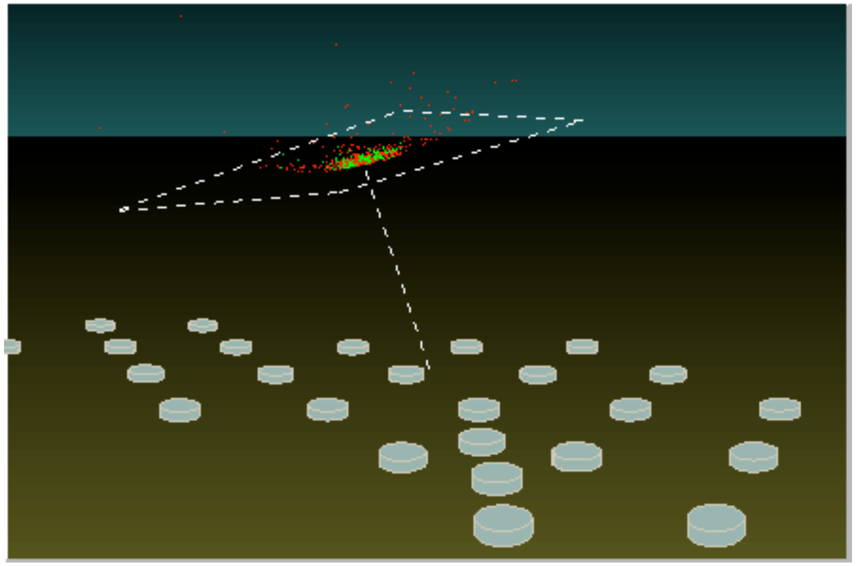
Graph from [2]

- Some events may have been observed above 7 x $10^{19}$ eV with no sign of the GZK cutoff
- This was not expected
- If the Ultra High Energy Cosmic Rays (UHECRs) are protons and nuclei, from extragalactic sources, an energy cutoff should be present.
- Protons with an *initial* E > $10^{20}$ eV from >100 Mpc should appear at a lower energy due to energy loss to the CMB.



# Pierre Auger Observatory

- Goals of the Pierre Auger Observatory include:
  - See if there is a GZK suppression of UHECR (Ultra High Energy Cosmic Rays)
  - See if cosmic rays are isotropic



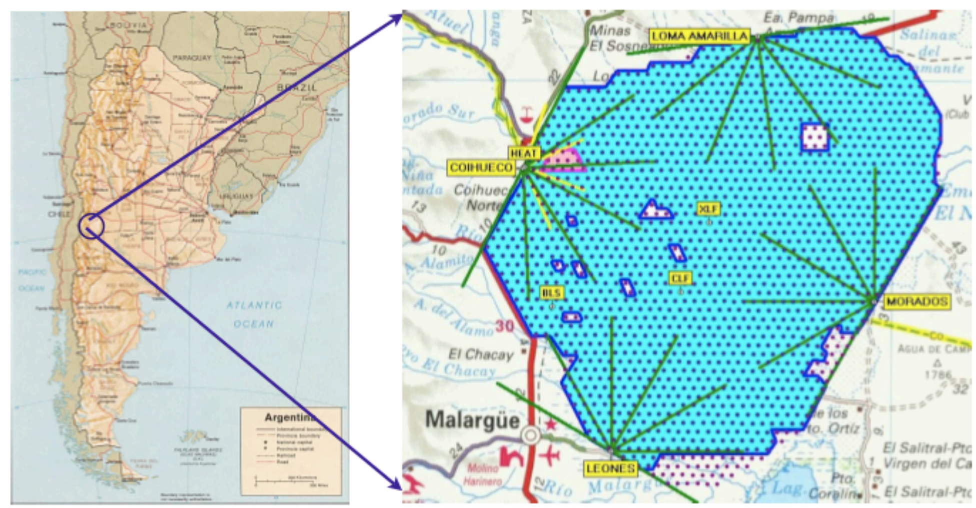
**Click on image to see EAS animation of Pierre Auger Cosmic Ray Observatory Array**
**(Must be online to view animation)**

# Pierre Auger Observatory

- Above $10^{19}$ eV, the arrival rate is only 1 particle per square kilometer per year.
- Cosmic rays with energies above $10^{20}$ eV have an estimated arrival rate of only 1/km$^2$ per century!
- Need huge area!!!!
- The Pierre Auger Observatory detection area of 3000 square kilometers!

http://www.auger.org

- South: Malargüe, Mendoza, Argentina ~ 3000 km$^2$, completed
  - Hybrid: 4 air fluorescence telescopes & 1600 water Cherenkov detectors
- North: planned in SE Colorado, USA ~ 20 000 km$^2$



# Pierre Auger Observatory

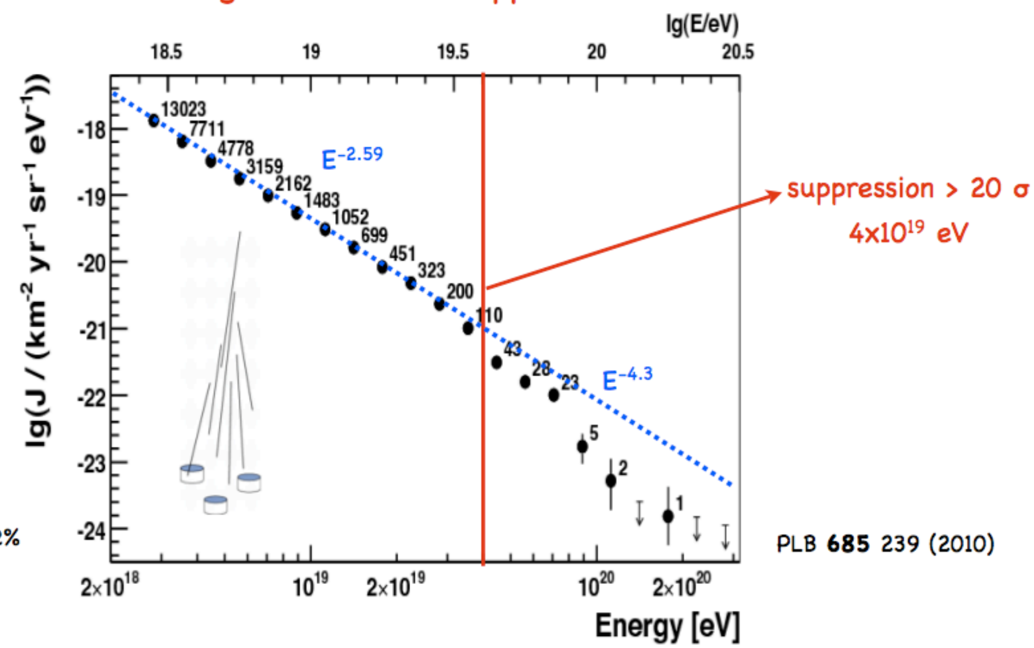
- The Auger Observatory is a "hybrid detector," employing two independent methods to detect and study high-energy cosmic rays.
- One technique detects high energy particles through their interaction with water placed in surface detector tanks.
- The other technique tracks the development of air showers by observing ultraviolet light emitted high in the Earth's atmosphere.

On the hill is one of the 4 Fluorescence Detector buildings and communications tower. In the bottom foreground is one of the 1,600 Surface Detectors.

# Auger Observatory observes a suppression of “GZK” particle flux

UHECR spectrum

Auger observes a suppression




syst. energy uncertainty 22%

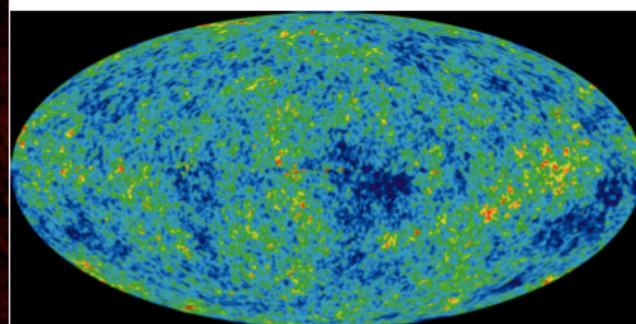
PLB **685** 239 (2010)

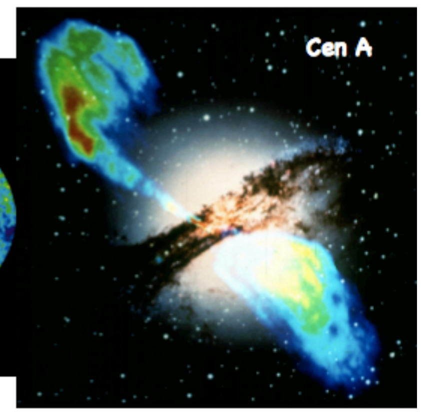
- updated spectrum for the surface detector
- data taken: Jan 2004 – Dec 2008, 12 790 km$^2$ sr yr

# Auger Observatory also observed anisotropy

- Flux suppression observed at highest energy (> $4 \times 10^{19}$ eV)

- Highest energy cosmic rays (> $5.5 \times 10^{19}$ eV) have correlation with nearby AGNs

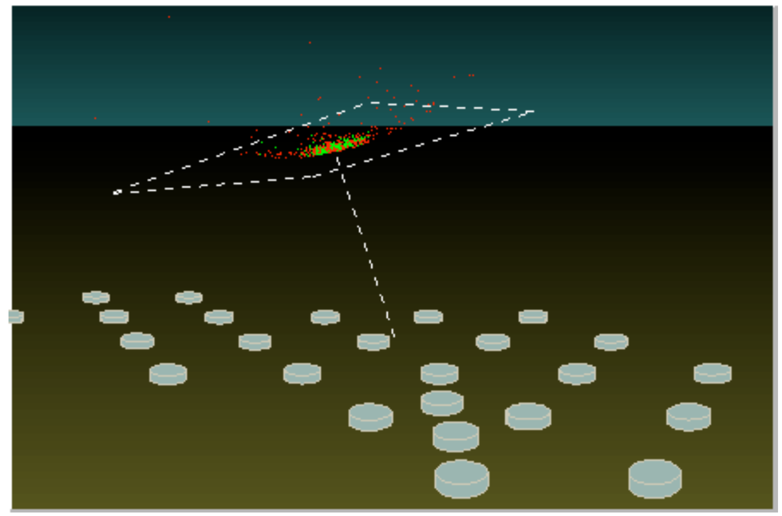



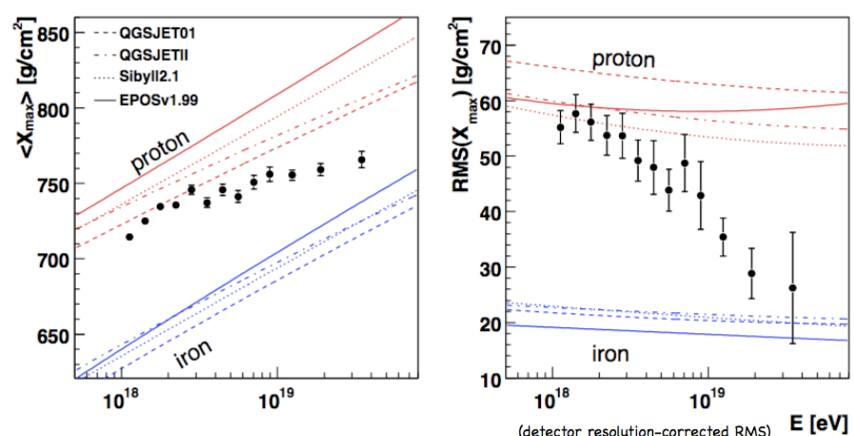



- protons can escape accelerator without much energy loss
- protons are abundant and stable
- heavier nuclei disintegrate in the source (& during propagation)

# But while Auger disproved the original "unexpected" result, it uncovered a new unexpected result!

- $X_{max}$ is the atmospheric depth at which the air shower creates the maximum number of particles.
- $X_{max}$ is sensitive to the composition of the cosmic ray (mass).
- Therefore $X_{max}$ can indicate if the initial cosmic ray was a proton or a heavier particle (for example, Fe).
- The NEW unexpected observation is that the higher energy particles may be Fe, not protons.



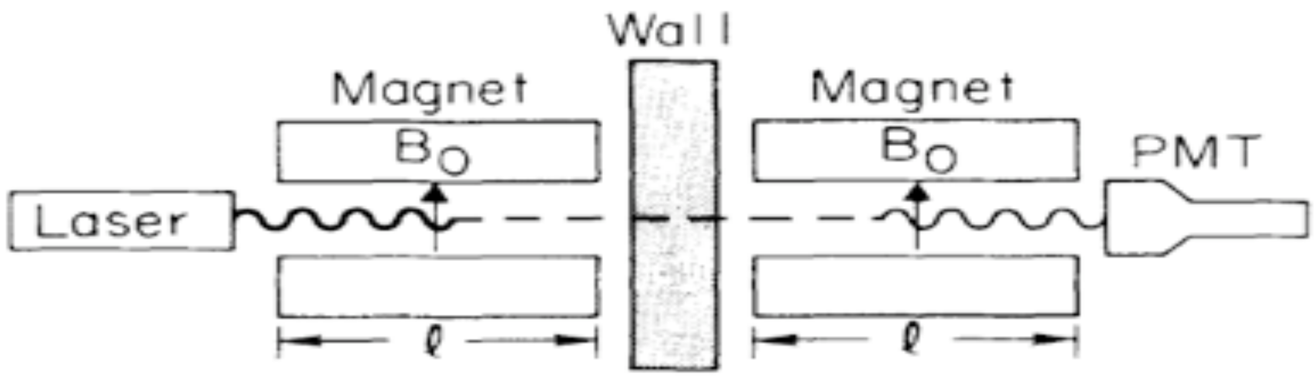


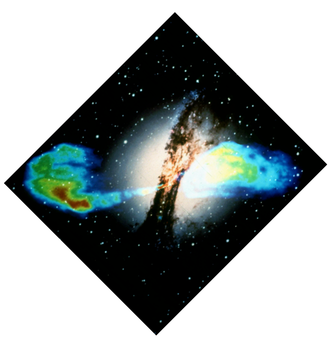

PRL **104** 091101 (2010)

GammeV

# GammeV

GammeV wants to see if photons oscillate into axions, go through the wall (simulating the IR background), and then oscillate back into photons.

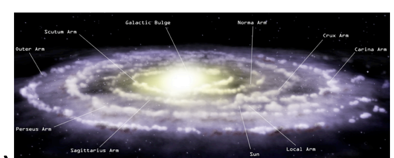


Very High
Energy
photon
(gamma ray)


Very High
Energy
photon
(gamma ray)

Milky Way

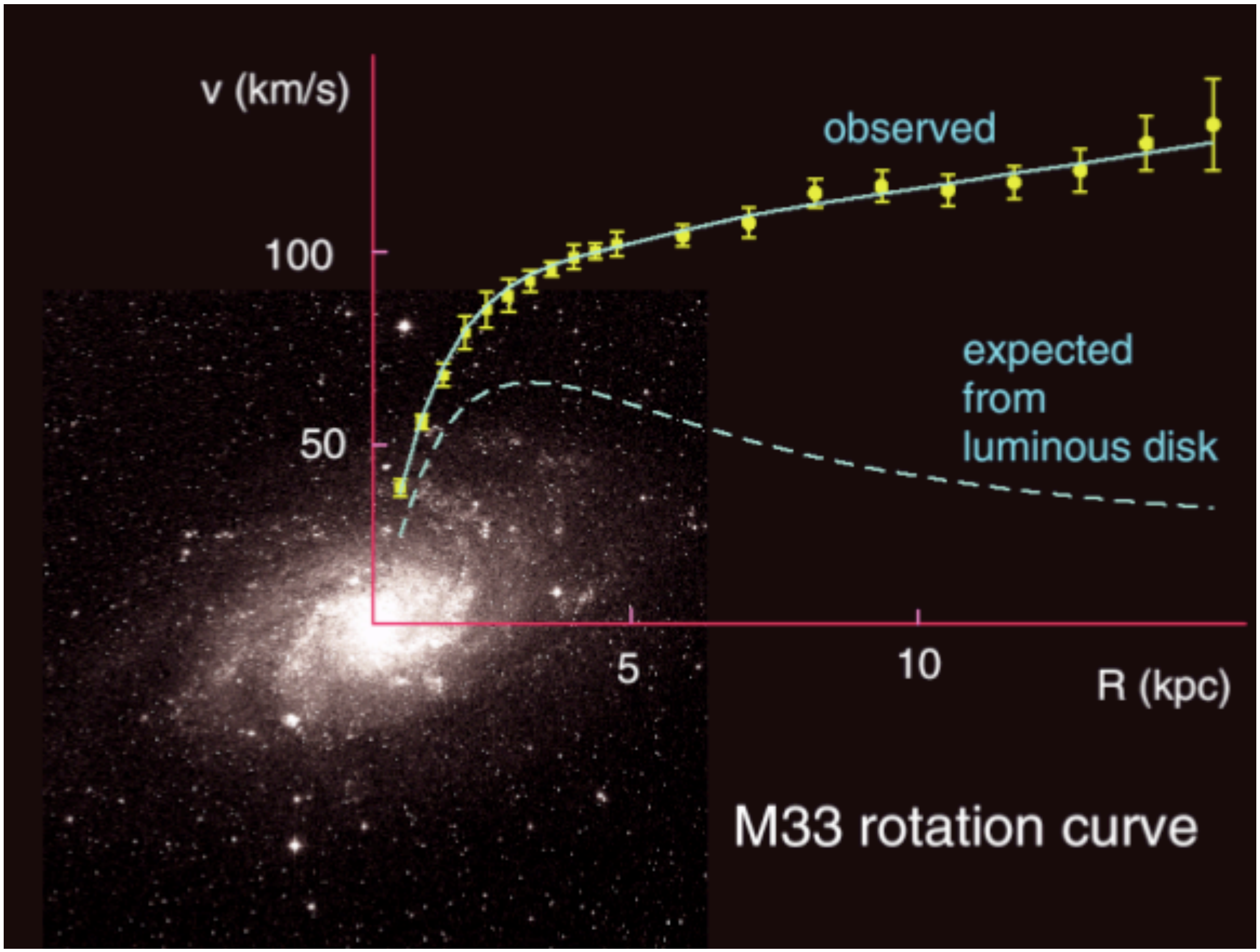


# Dark matter

# What was unexpected?

- Cosmic Microwave Background — Unexpected noise
  - R&D: QUIET (Q/U Imaging ExperimenT)
- Physics at high energy scales — Unexpected transparency
  - Pierre Auger Observatory
  - GammeV
- Dark matter — Unexpected flat rotation curves
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe
- Dark energy — Unexpected accelerated expansion
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

# Unexpected flat rotation curves of galaxies



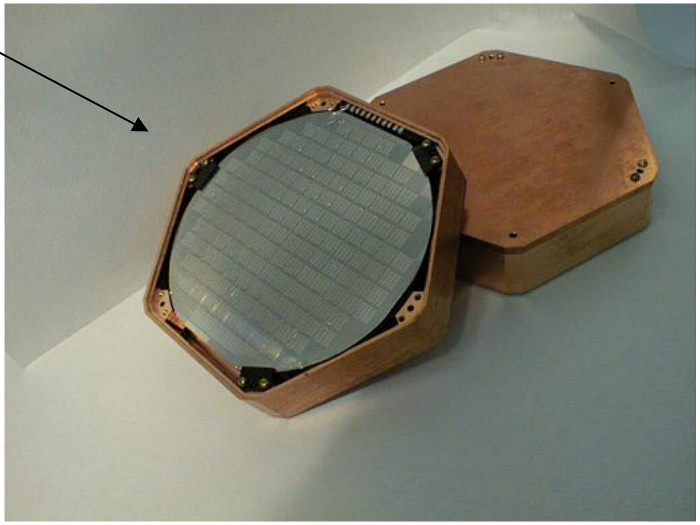
# Direct detection of dark matter

- Exotic new particles, like WIMPs (Weakly Interacting Massive Particles) may comprise the dark matter

- One way to look for WIMPs is via direct detection of the WIMP-nucleus scattering

# CDMS

- Look for the elastic scattering of WIMPs off nuclei in a low-background target detector.
- The Cryogenic Dark Matter Search (CDMS) experiment uses detectors of ultrapure germanium and silicon operated at a temperature of 20 mK.
- The simultaneous measurement of both ionization and phonon signals allows nuclear recoil events to be differentiated from other particle interactions

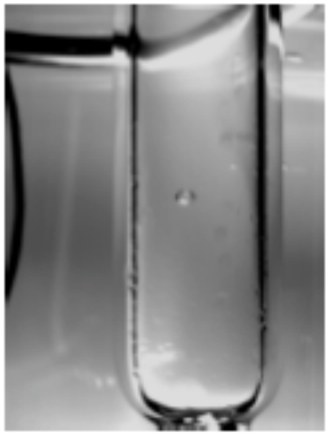


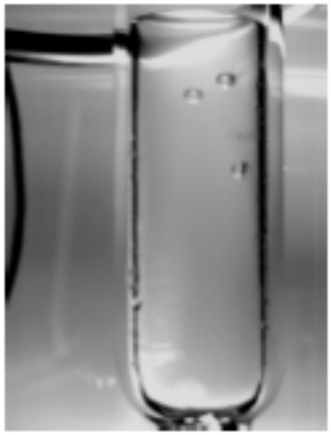
*CDMS Cryogenic Dark Matter Search*

# COUPP

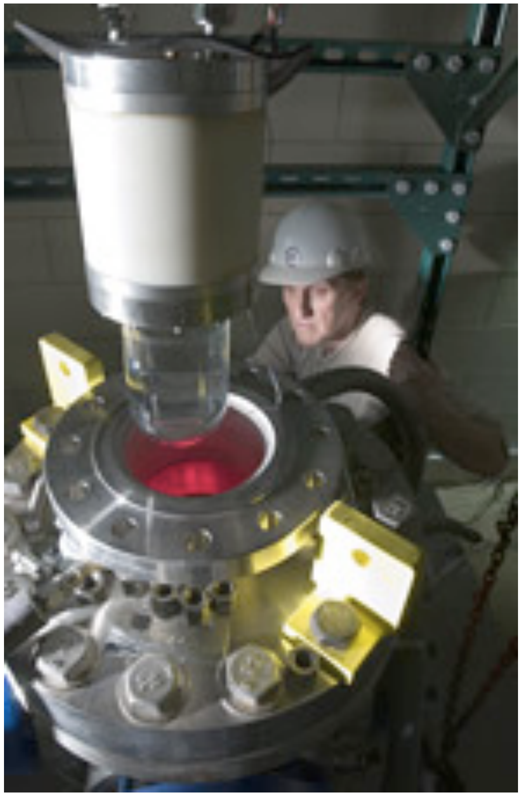
- COUPP uses stable room-temperature bubble chambers to search for WIMPs

- Look for the elastic scattering of WIMPs off $CF_3I$



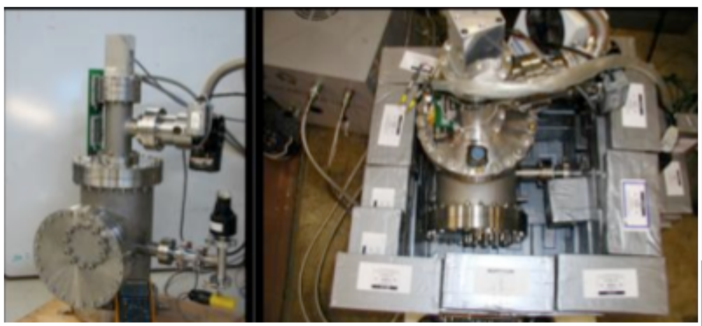


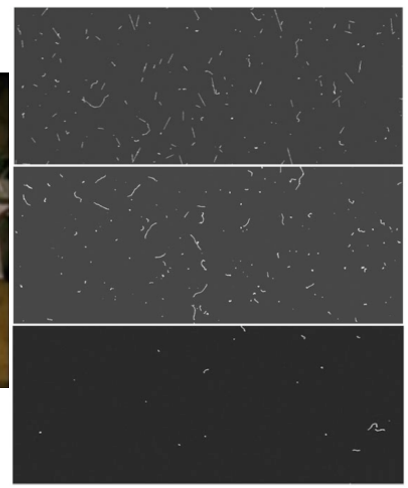
A nuclear recoils in COUPP bubble chamber



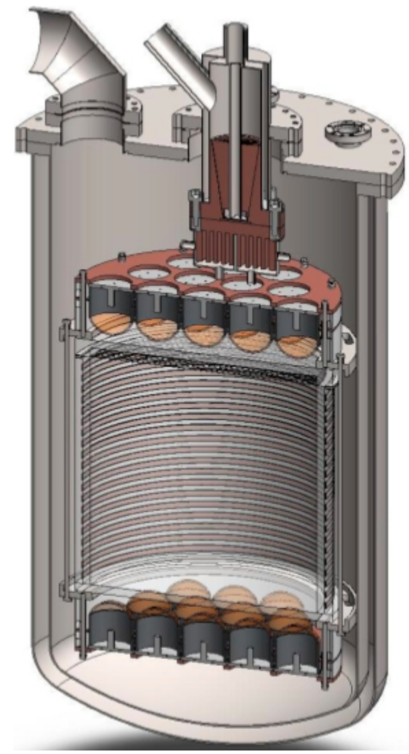
# DAMIC, Ar TPC, solid Xe

- Other dark matter detectors being developed at Fermilab have other materials for the recoil target.





DAMIC uses Si CCDs as the recoil target



LAr TPC

# Dark energy

# What was unexpected?

- Cosmic Microwave Background — Unexpected noise
  - R&D: QUIET (Q/U Imaging ExperimenT)

- Physics at high energy scales — Unexpected transparency
  - Pierre Auger Observatory
  - GammeV

- Dark matter — Unexpected flat rotation curves
  - CDMS (Cryogenic Dark Matter Search)
  - COUPP (Chicagoland Observatory for Underground Particle Physics)
  - R&D: DAMIC (DArk Matter in CCDs), Ar TPC, solid Xe

- Dark energy — Unexpected accelerated expansion
  - SDSS (Sloan Digital Sky Survey)
  - DES (Dark Energy Survey)

What keeps the ride going?

Dark Energy.

# The Dark Energy Survey

# Dark Energy Survey
# (DES)

- Goal: Learn why the universe seems to be expanding *faster* and *faster*.

- Build a new 500 Megapixel camera, the Dark Energy Camera (DECam) and wide field corrector to be used on the 4-meter Blanco telescope at Cerro Tololo Inter-American Observatory in Chile.

# DES requirements

DES combines 4 probes of Dark Energy

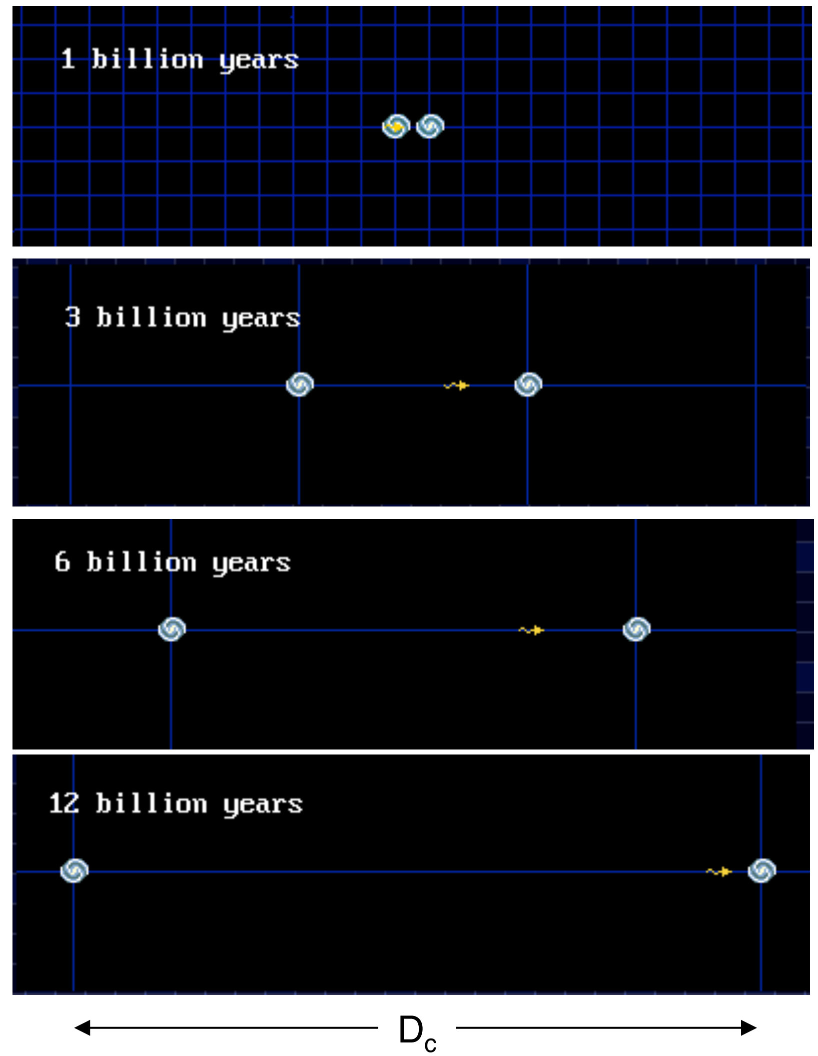
- Weak Gravitational Lensing
  Shapes of ~300 million source galaxies
- Galaxy Cluster Counts
  ~100,000 galaxy clusters to z > 1
- Baryon Acoustic Oscillations
  Clustering of ~300 million galaxies to z = 1 and above
- Type Ia Supernovae
  ~3000 Type Ia SNe to z ~ 1

Blanco telescope

# How far is z=1?

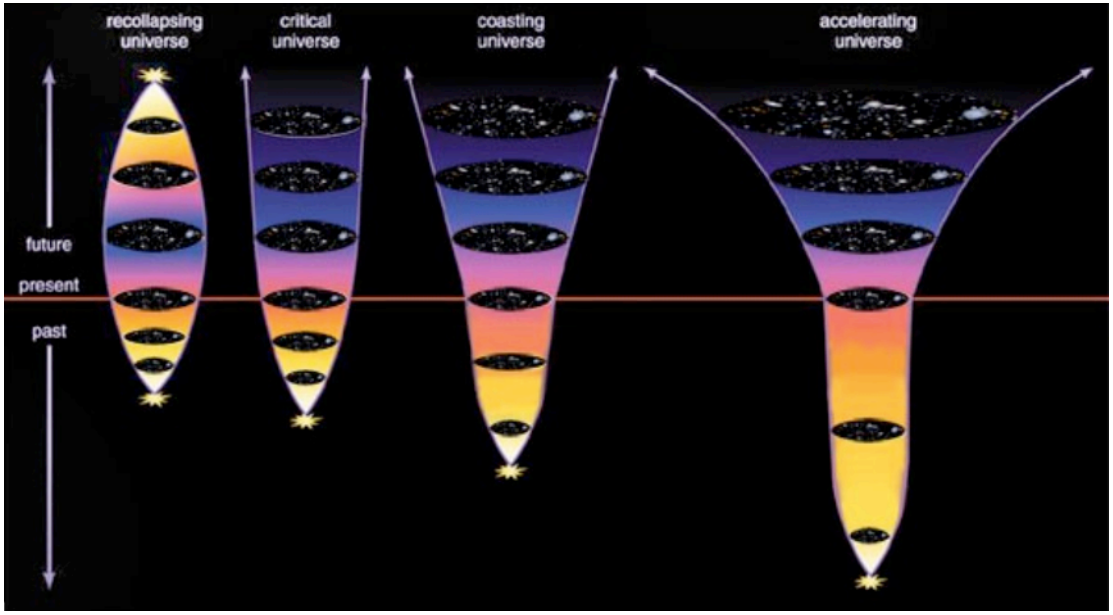
- “DES will count ~100,000 galaxy clusters to z > 1"
- What that really means is:
- "There are 100,000 clusters between us and a comoving distance, $D_c$, of 3317.3 Mpc. that are bright enough for DES to detect."
- The comoving distance is the distance to the object NOW (or at the time of the observation).

1 Parsec (pc) = 3.26163626 light year



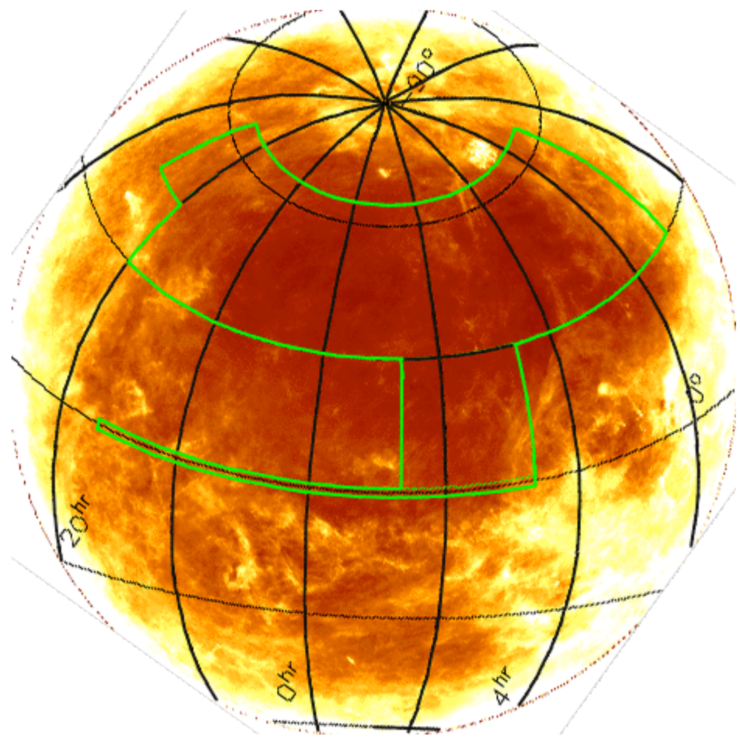
# How does the survey work?

- The supernovae will give us an independent measure of expansion with a new dataset, similar to what other surveys have done but out to a larger distance.
- How the density of galaxies varies with distance will also tell us how the universe has changed over time and thus whether the expansion we see has been constant over that time.



# How does the survey work?

- Take data for about 100 nights each year for 5 years
  - The survey area is visible from Oct-Feb
- Obtain about 300 images per night
- 100 seconds + 17 second readout time
  - This is driven by the desire for 8 tilings/ observing season: to observe the survey area 8 times/season.
- Send data to NCSA (National Center for Supercomputing Applications) at University of Illinois for processing
- Raw dataset: ~150,000 images
- Processed dataset: > 1 petabyte of data




DES survey area is outlined in green

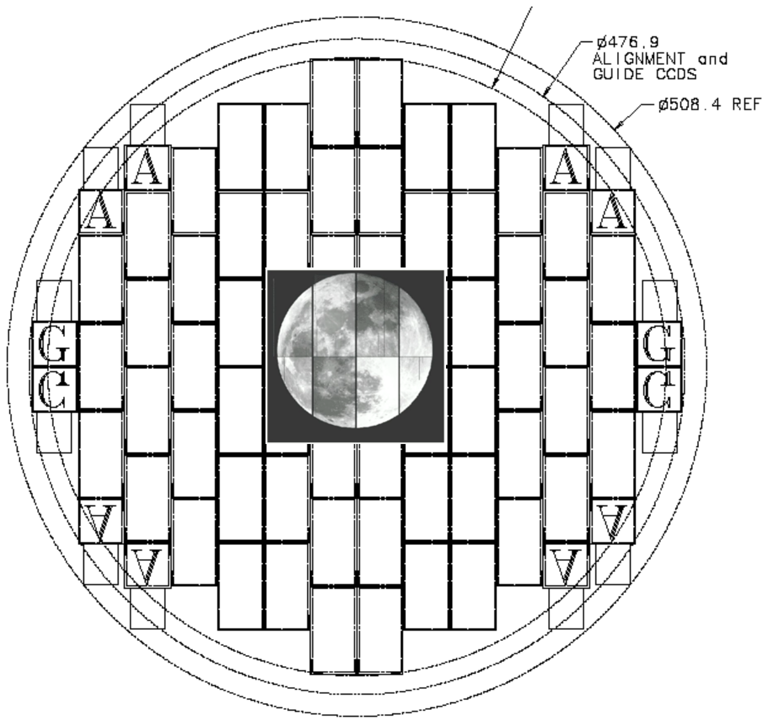
## How will the data get from the telescope on the mountain in Chile to the data archive and processing center at NCSA at UIUC?

- It's network the whole way.
- Wireless from the mountain to La Serena and cable thereafter.
- The entryway to the US is through Miami.
- Need to average ~36 Mbps over 18 hour period to return a typical DES night.
- There are hopes to have something more like 100 Mbps.

# DES requirements

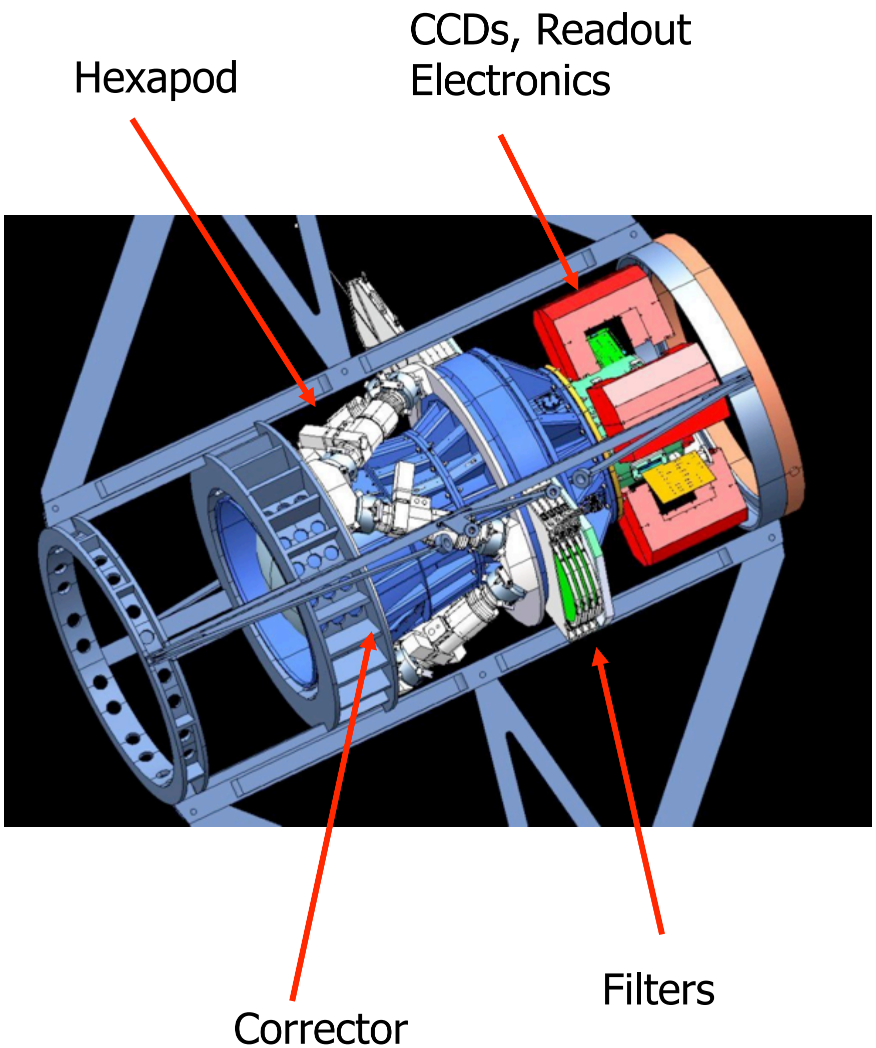
- For a sky survey, need wide field optics
  - Convert the Blanco to a 3 square degree field of view.
- For a deeper (z>1) survey, need red-sensitive CCDs
  - Use LBNL thick, high-resistivity CCDs
  - By making the CCD thicker, it is easier to detect a red light.

DECam Focal Plane




62 2kx4k Image CCDs: 520 MPix
8 2kx2k focus, alignment CCDs
4 2kx2k guide CCDs

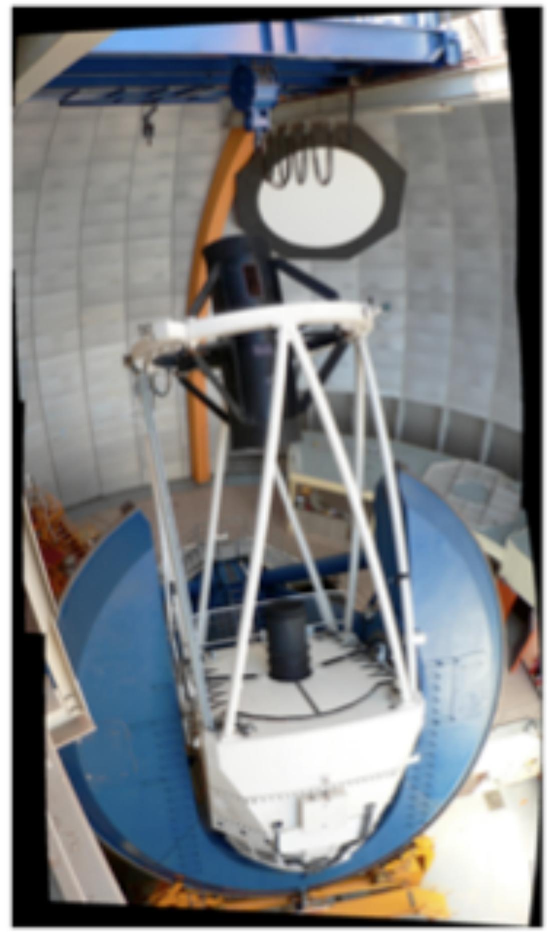
# New optics + New CCDs = DECam



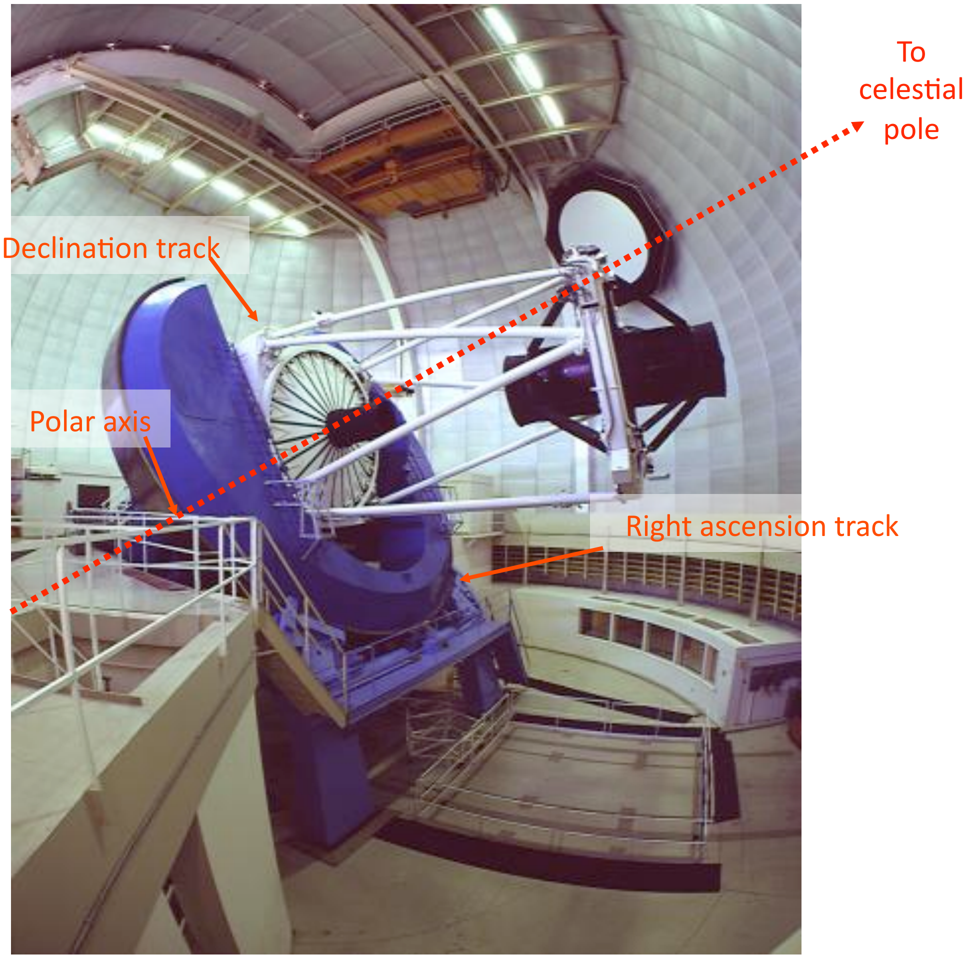

- The major components
  - 520 megapixel CCD camera
  - Low noise read-out system
  - Combination shutter-filter system
  - Wide field optical corrector (3 square degree field of view)
  - Hexapod to provide adjustability

## New optics + New CCDs = DECam

- The DECam instrument will replace the entire prime focus cage of the Blanco.



# Equatorial mount



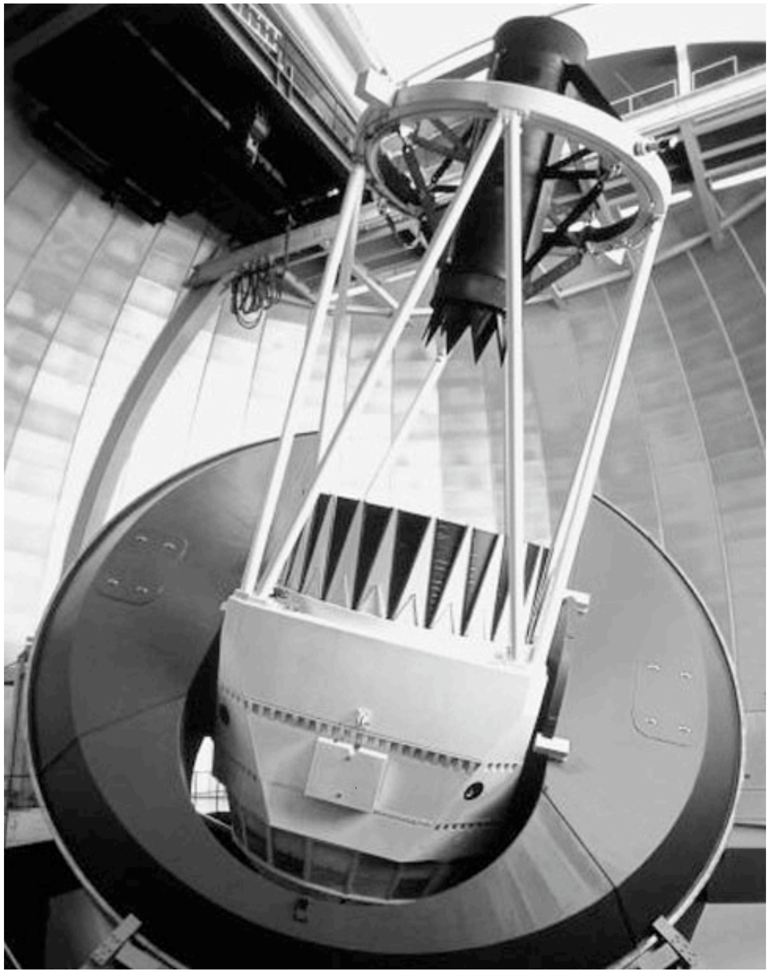

Blanco 4-meter telescope

1/24 scale desktop model of the Blanco

## Why use the Blanco telescope?

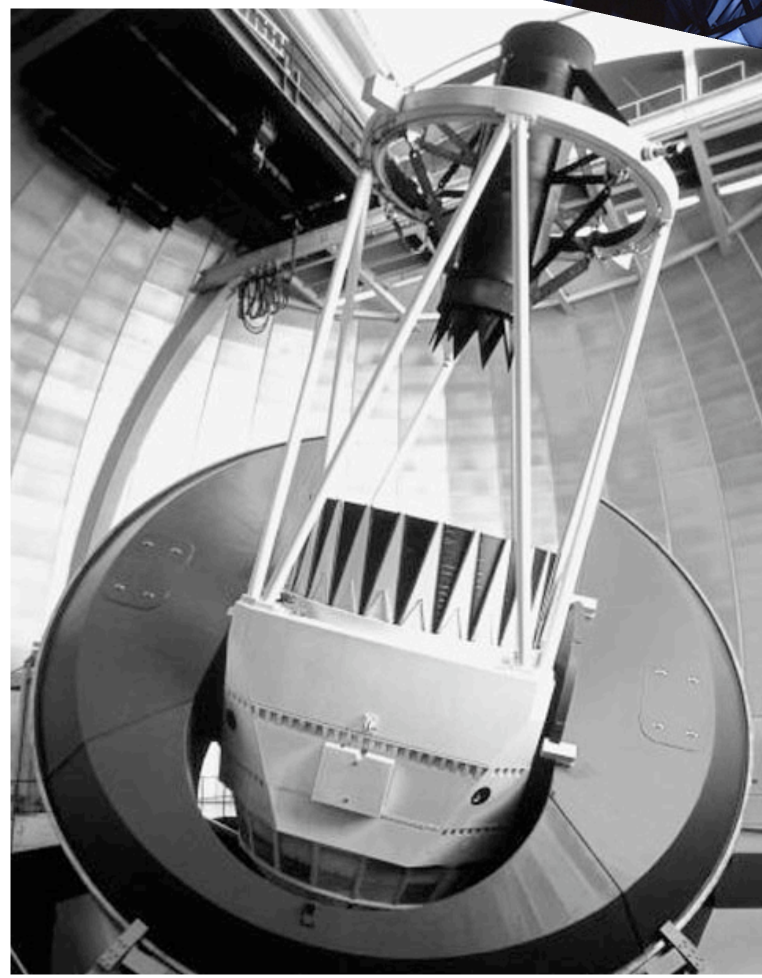
- The reason DECam is going on the Blanco is that NOAO offered, through a public announcement of opportunity, 30% of the Blanco time in exchange for a new instrument.

- No such offer was available for other telescopes.



## Why use the Blanco telescope?

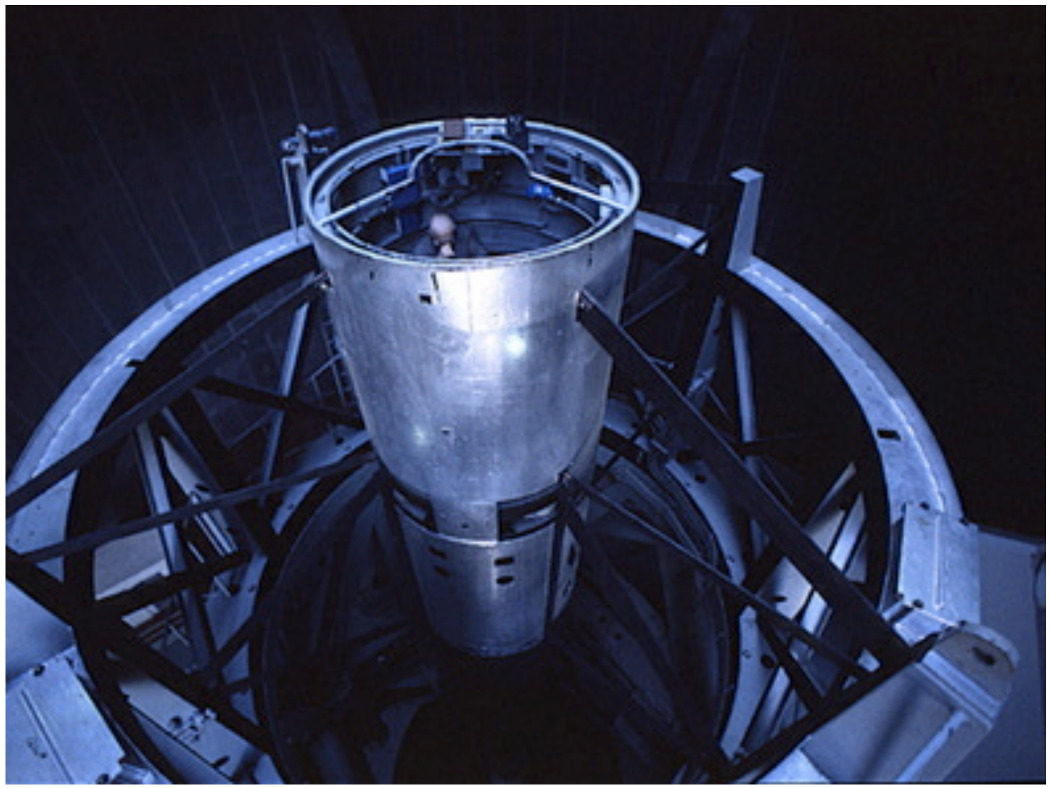
- The Blanco is also ideally suited to getting a new prime focus instrument because it was built to handle a large load at the top end.
- When it was built, people rode in the cage and took pictures on glass photographic plates.
- Now, DECam will be taking pictures of roughly the same size with CCDs.



# Example of observing from a prime focus cage


- *"Each time you go up, you carry a lot of paper. You carry some photographic plates in a tiny little box, and you carry a whole set of dreams of what the object you're going to work on is going to turn out to be."*
- *Voice of Jesse Greenstein, Cal Tech astronomer*
- *Picture is of prime focus cage of 200" Palomar telescope*

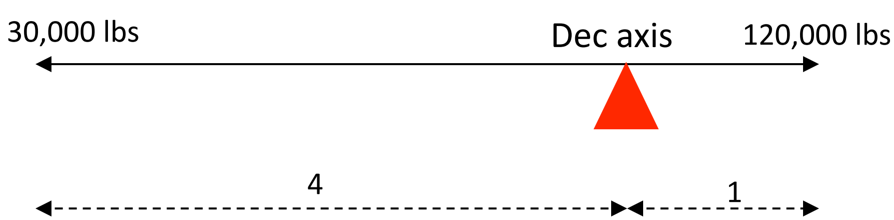
# Example of observing from a prime focus cage



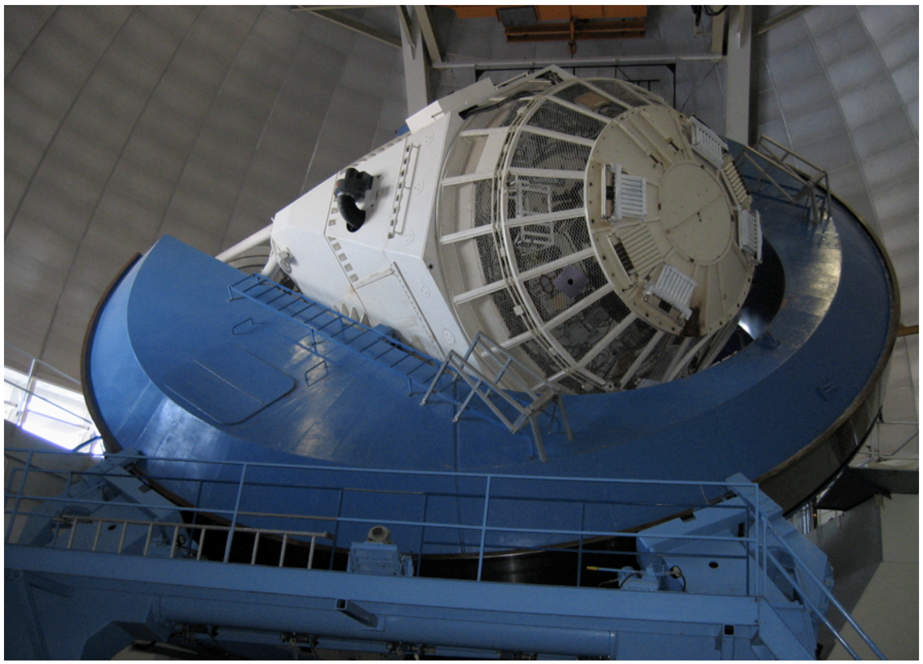
- *"Working a night in the small cage high above the primary mirror, feeling closer to the stars than the earth, remains an exhilarating and unforgettable experience."*
- *Voice of Jesse Greenstein, Cal Tech astronomer*
- *Picture is of prime focus cage of 200" Palomar telescope*

# How much does DECam weigh?

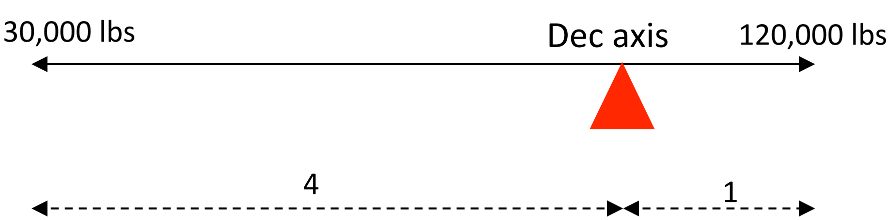
- The total weight of the upper structure is about 30,000 pounds.
- DECam weighs about 7,500 pounds.
  - DECam = corrector + imager + filter changer + shutter.
- The rest of the upper structure weighs about 22,500 pounds.
  - This includes the upper Surrier truss, outer ring, flip ring, fins, and prime focus cage



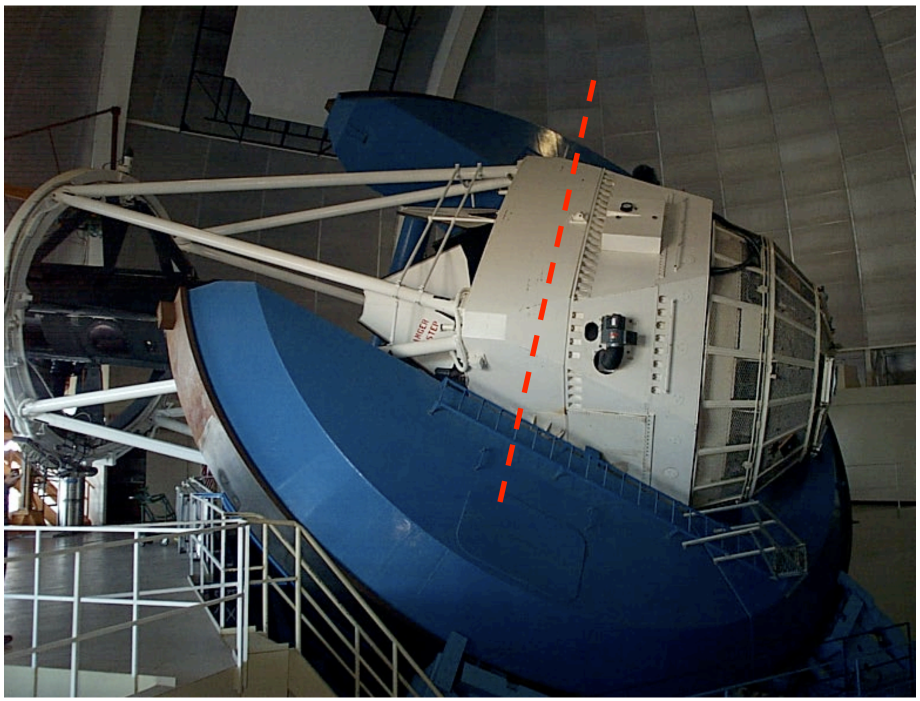
# How much does DECam weigh?

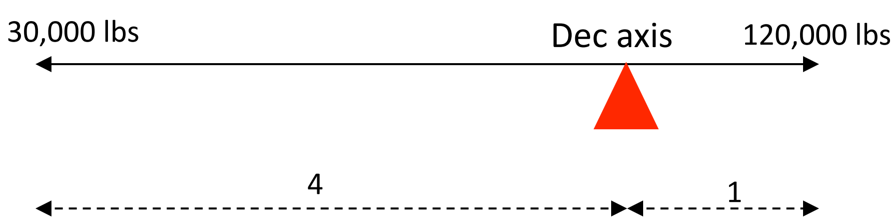


- The lower structure is comprised of the primary mirror, mirror cell, ring girder, and Cassegrain cage.
- The total weight of the lower structure is about 120,000 pounds.



# How much does DECam weigh?





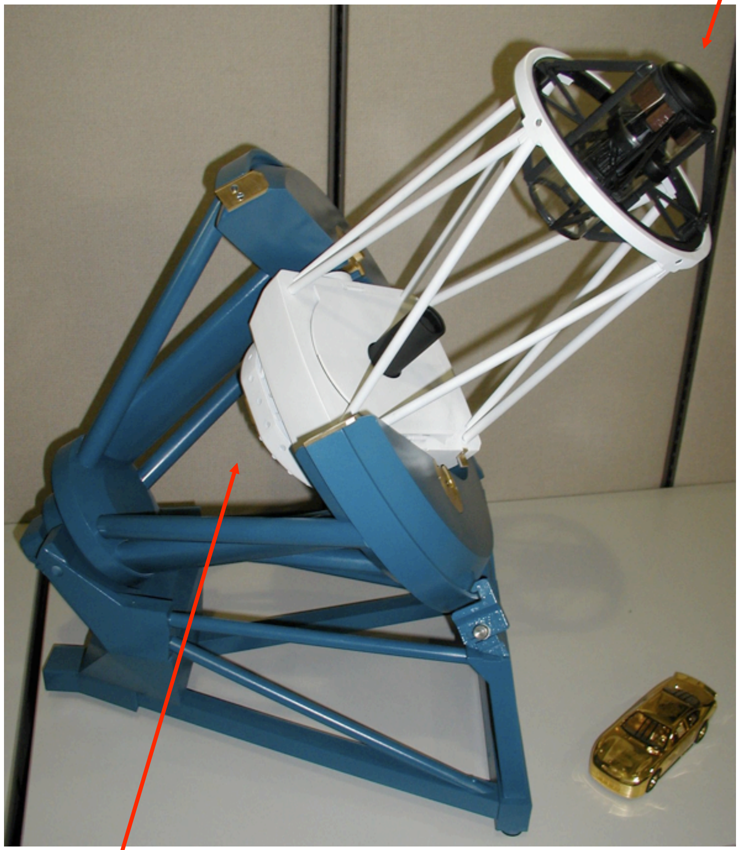

- The weight above the declination axis must be balanced by the weight at the opposite end of the 4:1 lever arm system.

$$(m_{upper}g) \times r_{upper} = (m_{lower}g) \times r_{lower}$$

$$30{,}000 lbs \times 4 = 120{,}000 lbs \times 1$$

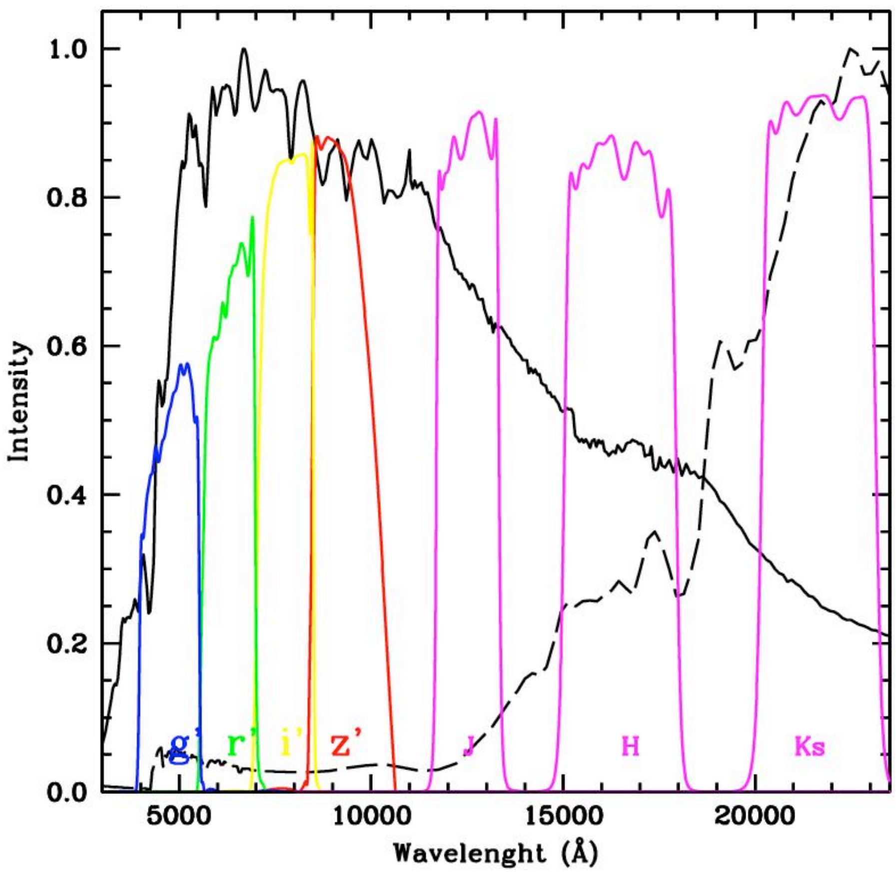
# Telescope usage

- DES is comprised of two multiband surveys
  - 5000 deg$^2$ *g, r, i, z, Y*
  - 40 deg$^2$ repeat (SNe)
- DECam will be used to perform the Dark Energy Survey with 30% of the telescope time over a 5 year period
- During the remainder of the time, and after the survey, DECam will be available as a community instrument.
- DECam is located at the f/2.7 prime focus of the Blanco telescope.
- Some users may prefer to use other cameras and instruments located at the Cassegrain focus, so provision must be made to install a secondary (f/8) mirror in front of DECam.



# Photometric redshifts

- The 5000 square degree area of DES will be surveyed twice per year per filter.
- The galaxy catalog will reach 24th magnitude and have photometric redshifts out to z~1.3
- The survey overlaps the Sunyaev-Zeldovich cluster survey of the South Pole Telescope and the infrared survey of the Vista Hemisphere Survey, which uses the Visual and Infrared Survey Telescope for Astronomy (VISTA)
- Information from VISTA's longer wavelength observations will improve the photometric redshifts.



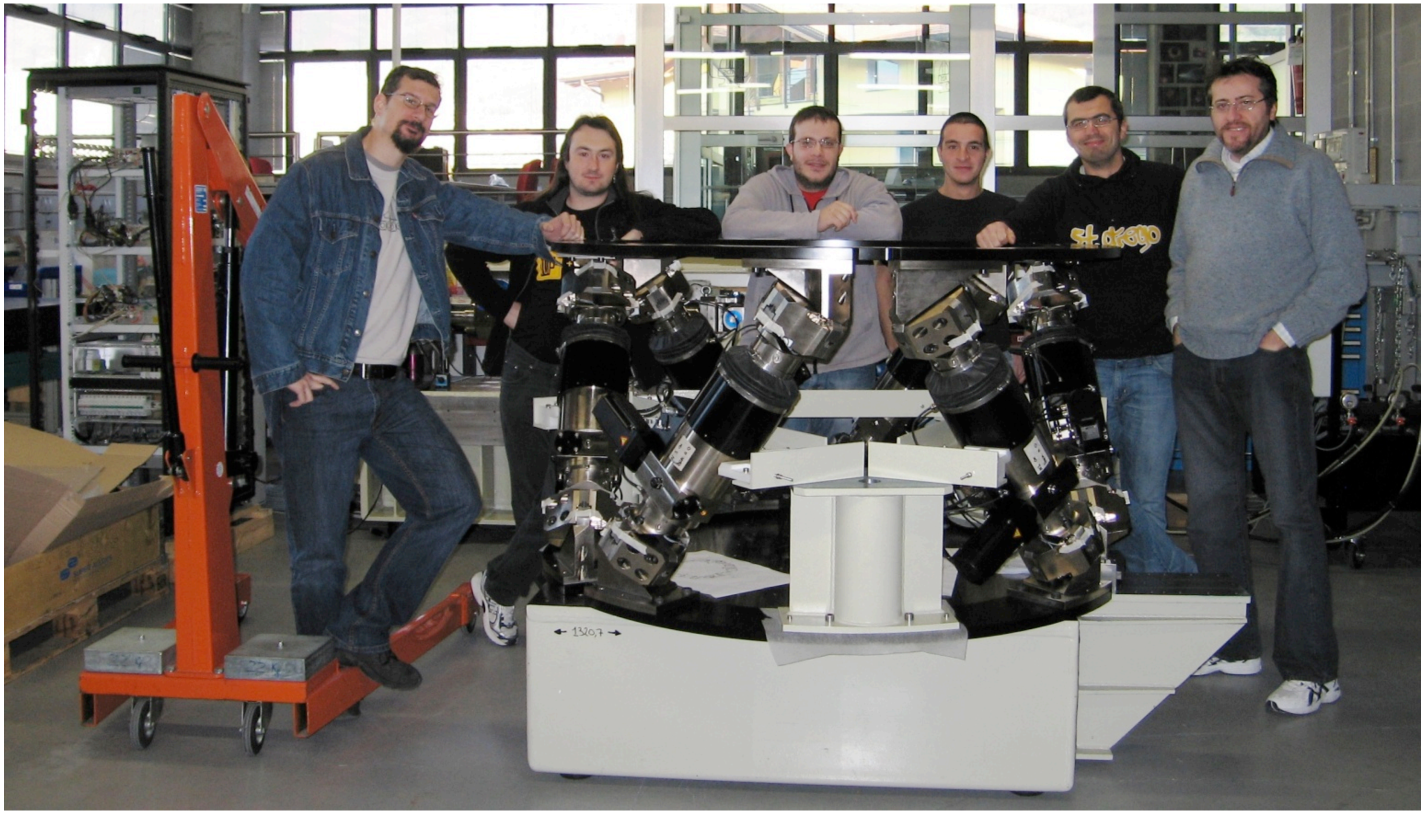
# Why isn't adaptive optics used?

- The large field of view (3 square degrees) of DES makes adaptive optics especially challenging and costly.
- Good location minimizes bad seeing:
  - Elevation: 2123 meters
  - The median seeing of 0.9 arc sec is sufficient for the proposed science
- Maintain focus & alignment using the hexapod. (Shown on next slide)
- The telescope's thermal environment was improved by installation of large ventilation doors & ventilation subsystems

Elevation: 2123 meters

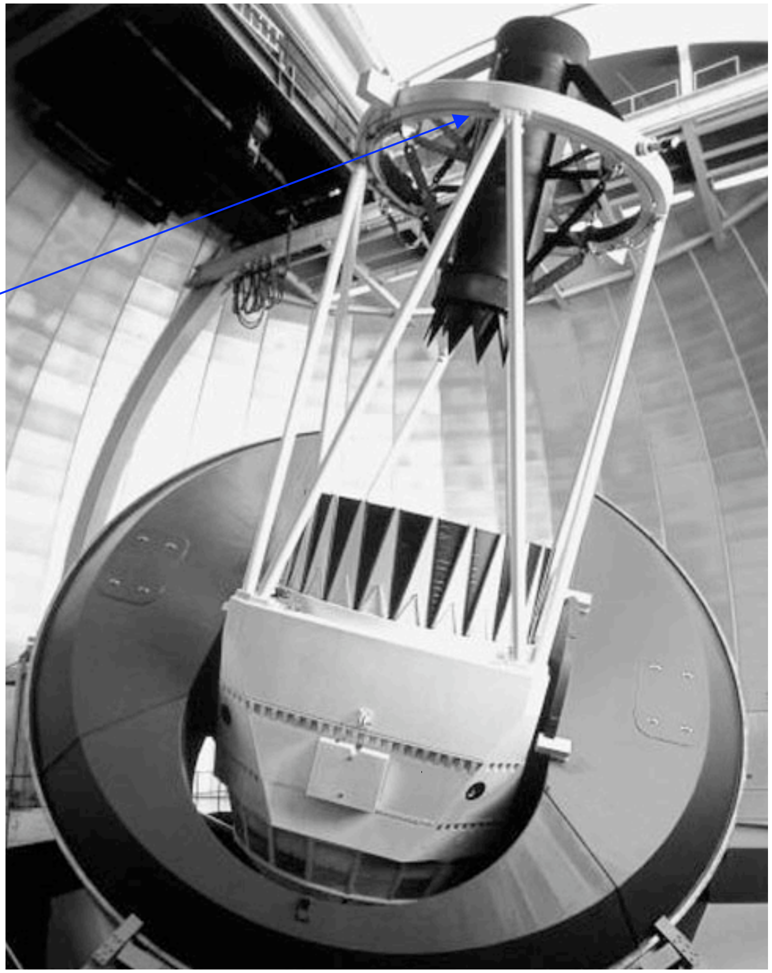
# Focusing the telescope

- The hexapod positions camera to 1 micron



# Correcting lenses

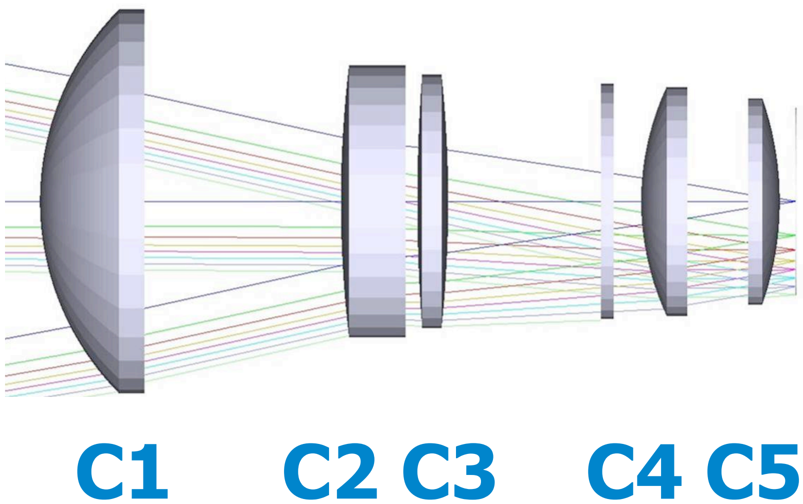
- Although the Blanco telescope has a hyperbolic primary, which helps eliminate spherical aberration and coma, the Dark Energy Survey requires such a large field of view (2.2 degrees) that a corrector is needed.



Blanco Telescope

# Correcting lenses

- The DECam corrector is comprised of 5 lenses, each uniquely shaped to correct for a variety of aberrations.
- Classically 3 corrector elements is a minimum.
- Corrections for all aberrations are folded into all the elements.
- Each element does not have one, unique function (for example, they can't be separated out so "simply" as C1 corrects for coma, C2 for astigmatism, etc)




Blanco corrector

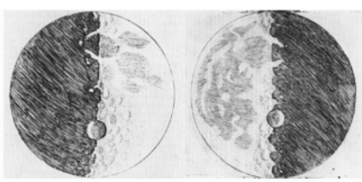
# Correcting lenses

- The DECam corrector consists of 5 fused silica lenses
- The last element serves as the window of the CCD vacuum vessel, so it is very close to the CCDs.
- High-potassium glass like BK7 cannot be used, because β rays from the decay of $^{40}K$ produced near the surface of the glass can strike the CCD.
- Lens fabrication is in progress.
- The blanks were completed in Jan. 2008 and the lenses are now being ground and polished at SESO in France.

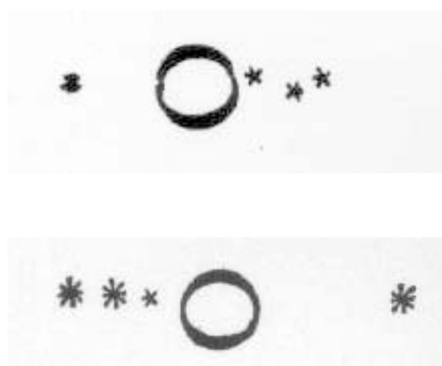
Blanco blank

# From Galileo to CCDs

- Galileo was the first to use the telescope systematically to observe celestial objects and to record and publish his observations.
  - Observations were by eye
  - Observations were recorded manually
  - Galileo published his observations in a short treatise entitled *Sidereus Nuncius* (*Starry Messenger*)



Moon



Jupiter's moons

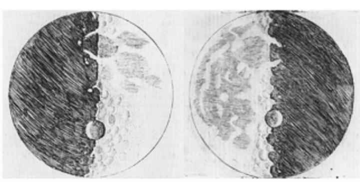
(referred to as Galilean moons)

The Pleiades

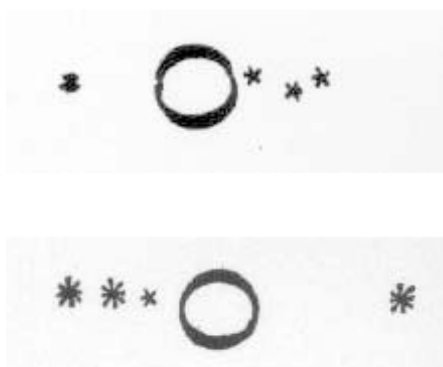
Showing more stars than are visible to the unaided eye.

# Galileo

- Notice that the objects Galileo viewed were “nearby”.
- Even if he stared longer and longer into the telescope, he could not see fainter and fainter objects.
- This is because the eye “refreshes” every 50-100 ms.



Moon



Jupiter’s moons

(referred to as Galilean moons)

The Pleiades

Showing more stars than are visible to the unaided eye.

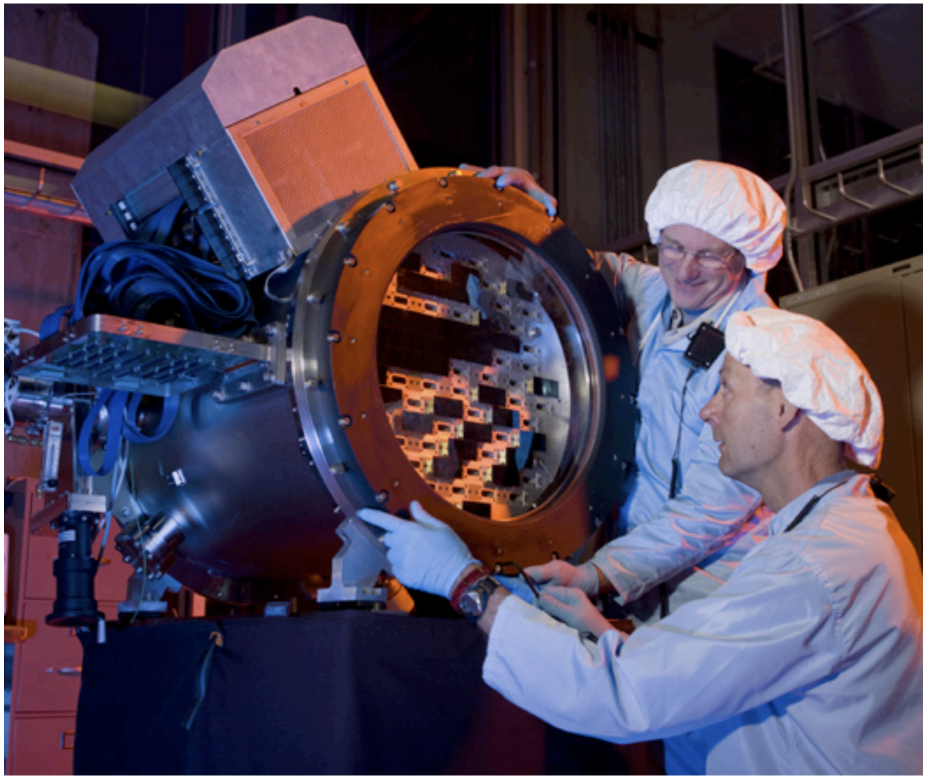
# Film rate

- Through experience in the early days of film, it was determined that a frame rate of less than 16 frames per second caused the mind to see flashing images.

- This is because persistence of vision depends on chemical transmission of nerve responses, and this biochemical process takes about 50-100 milliseconds.

# Photography and digital imaging

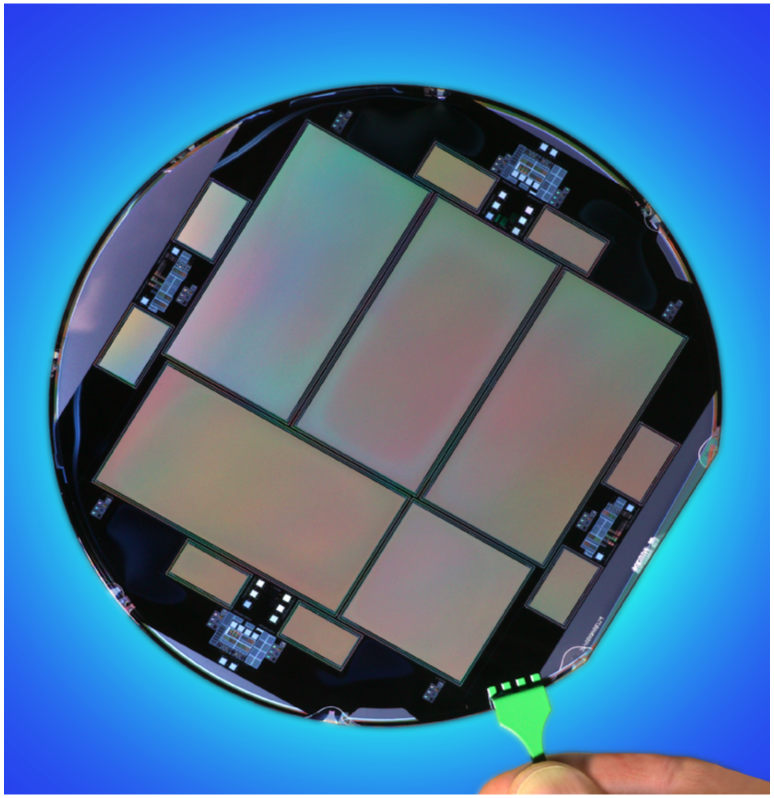
- However, photographic film and digital cameras CAN stare at the sky for a long time and store more and more light.
- Therefore, by replacing the human eye with cameras, we can detect fainter and more distant objects.



DECam focal plane and electronics

# New red-sensitive CCDs

- DES wants to observe distant objects.
- From Hubble's law, more distant objects are more highly -redshifted than nearby objects.
- Therefore, CCDs that can efficiently detects longer wavelength (redder) photons are desirable.
- DES CCDs are fabricated by Dalsa
- Further processing is done by Lawrence Berkeley National Laboratory (LBNL)
- Packaged and tested at Fermilab



# Thick CCDs

- The CCD developed by LBNL achieves high QE in the red and near-infrared by using a thick depleted region made possible by the use of a <u>high-resistivity</u> silicon substrate.

- Increase thickness -> increase ability to detect longer wavelengths

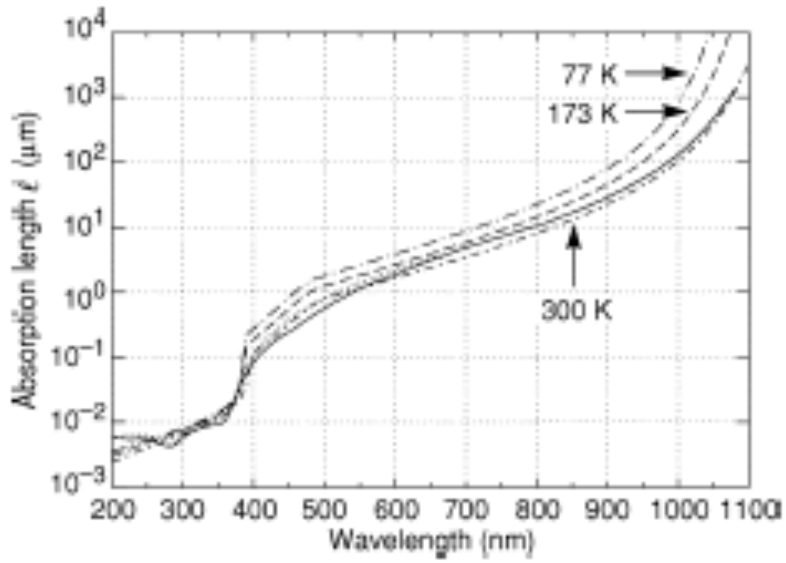
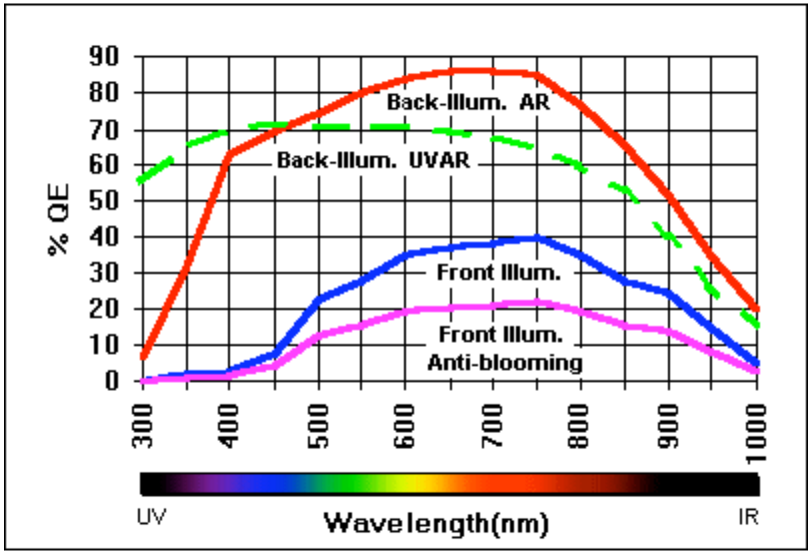


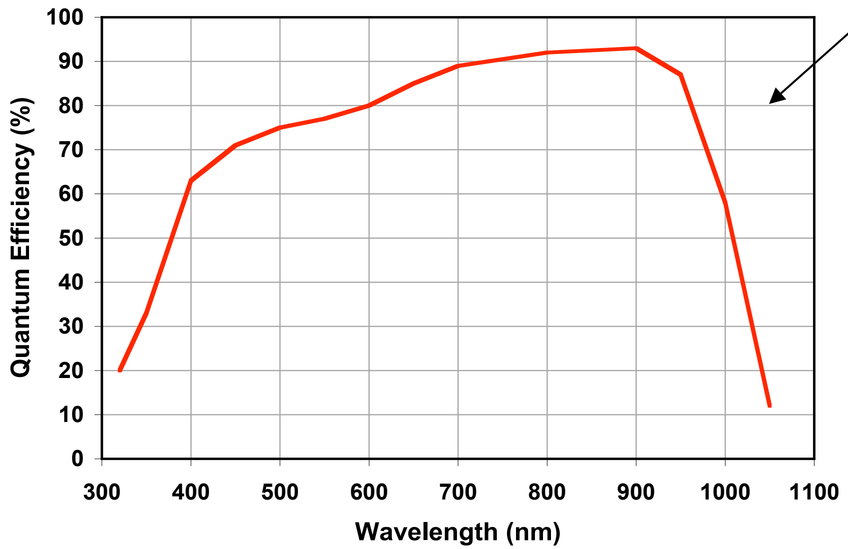

Fig. 2. Absorption length versus wavelength for silicon. Data and calculations (dashed lines) are taken from [18]. Additional room-temperature data (solid line) are taken from [1].

# QE of LBNL CCDs



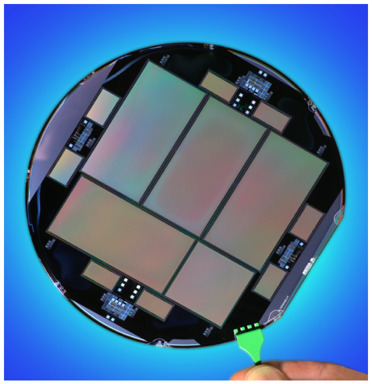

Typical Q.E. curves for
front- and back-illuminated CCDs

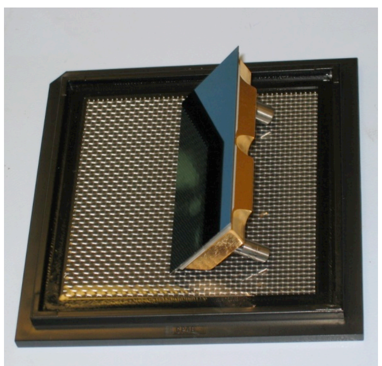
Much-improved IR sensitivity

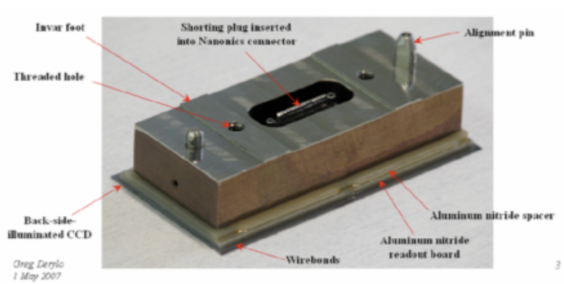


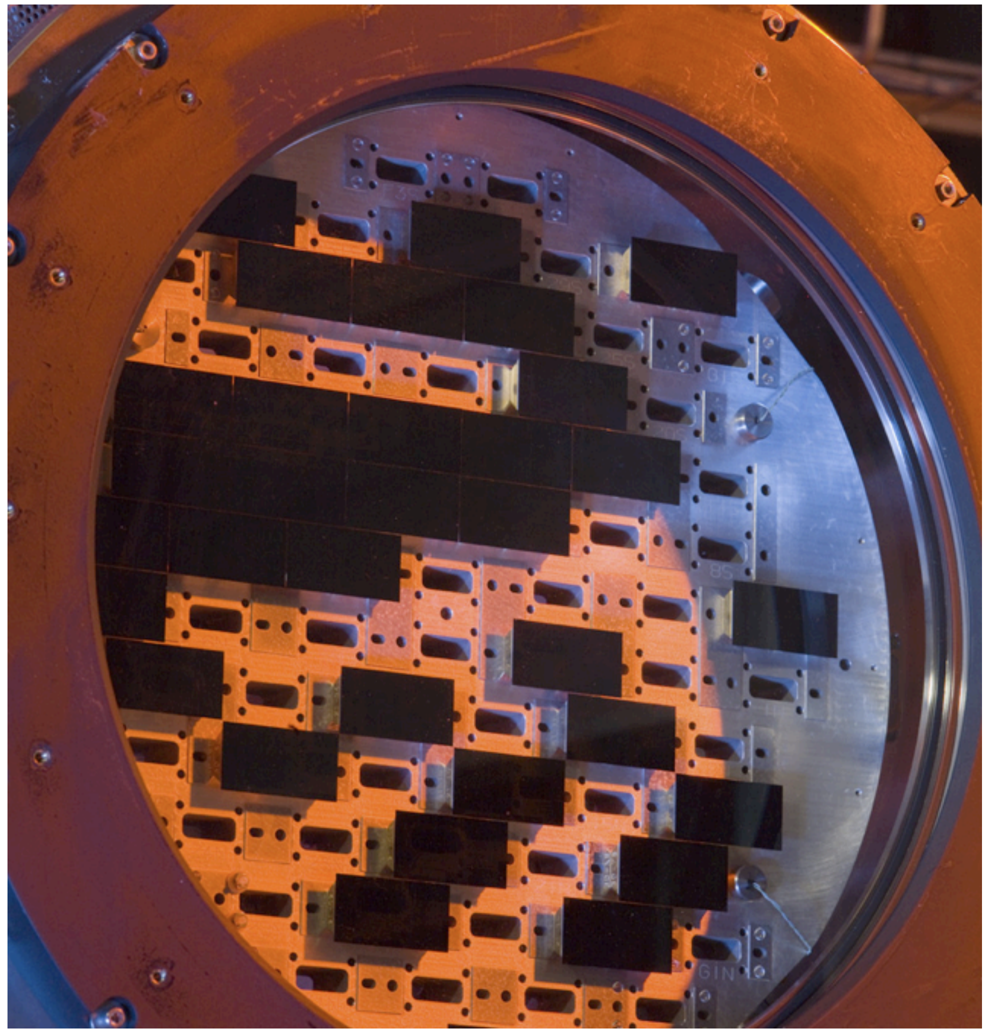

LBNL CCD QE

# From wafer to focal plane

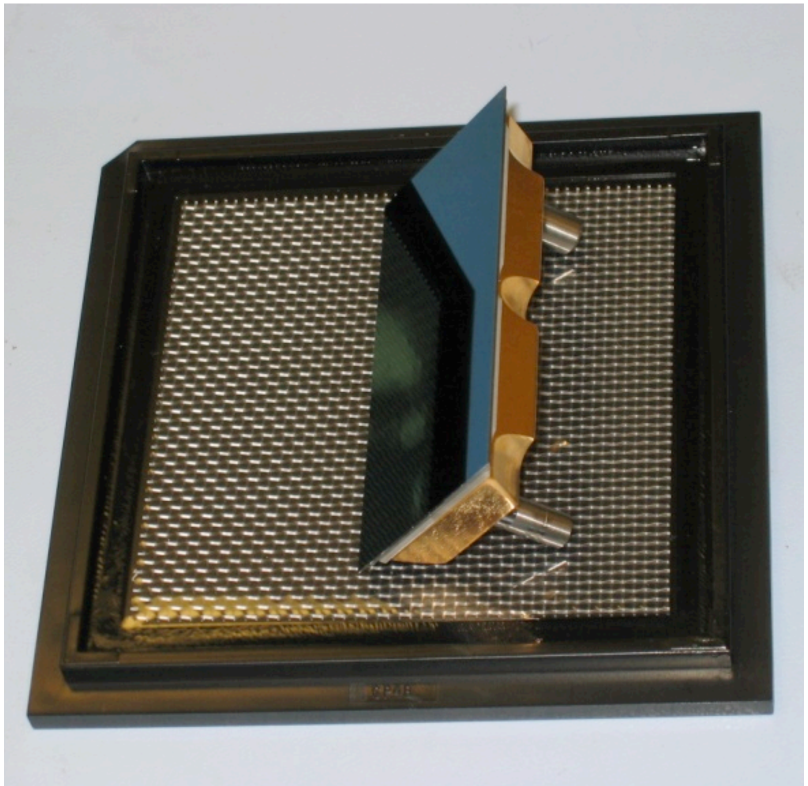
- 





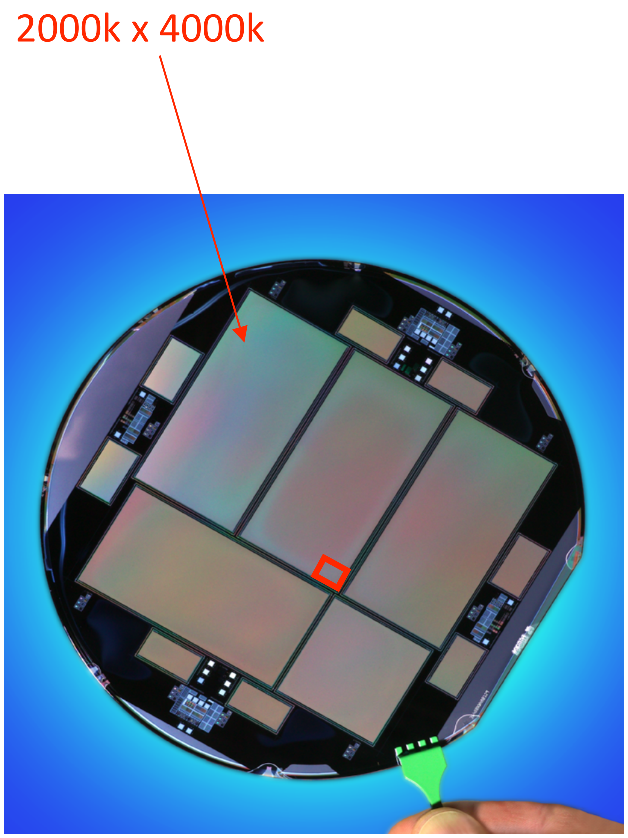



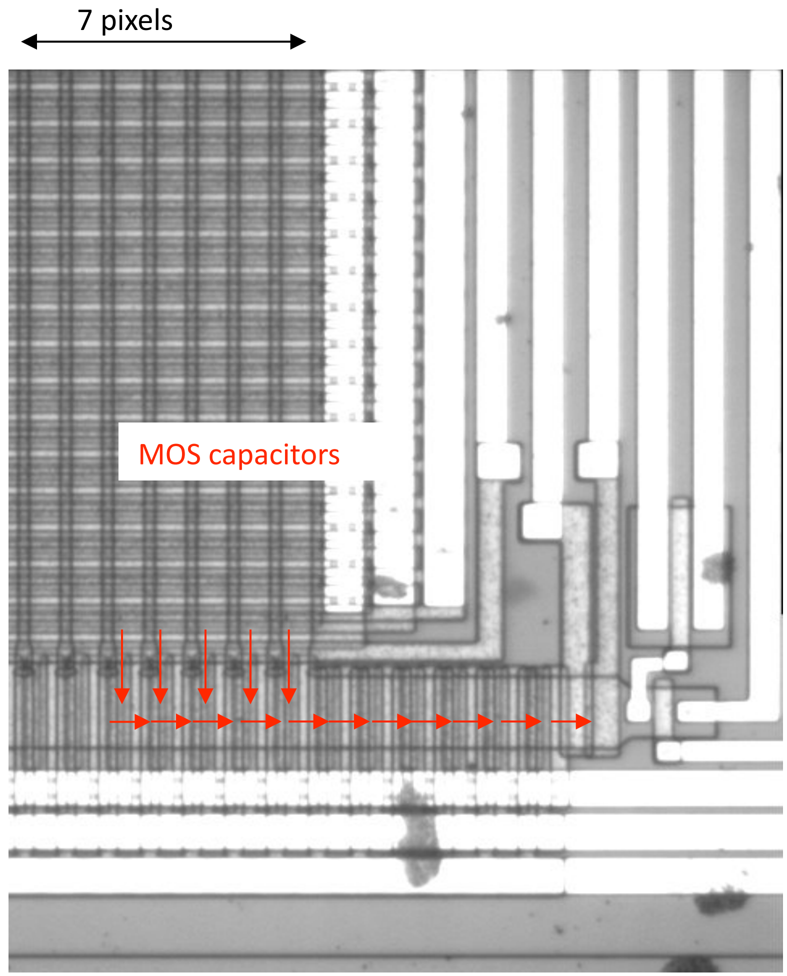
# DECam CCDs



| | DECam CCD Requirements |
|---|---|
| Pixel array | 2048 · 4096 pixels |
| Pixel size | 15 μm x 15 μm |
| # Outputs | 2 |
| QE(g,r,i,z) | 60%, 75%, 60%, 65% |
| QE Instability | <0.3% in 12-18 hrs |
| QE Uniformity in focal plane | <5% in 12-18 hrs |
| Full well capacity | >130,000 $e^-$ |
| Dark current | <~25 $e^-$/hr/pixel |
| Persistence | Erase mechanism |
| Read noise | < 15 $e^-$ @ 250kpix/s |
| Charge Transfer Inefficiency | $<10^{-5}$ |
| Charge diffusion | 1D σ < 7.5 μm |
| Cosmetic Requirements | <# Bad pixels> <0.5% |
| Linearity | 1% |
| Package Flatness | Effectively +-10 μm |

# CCD layout

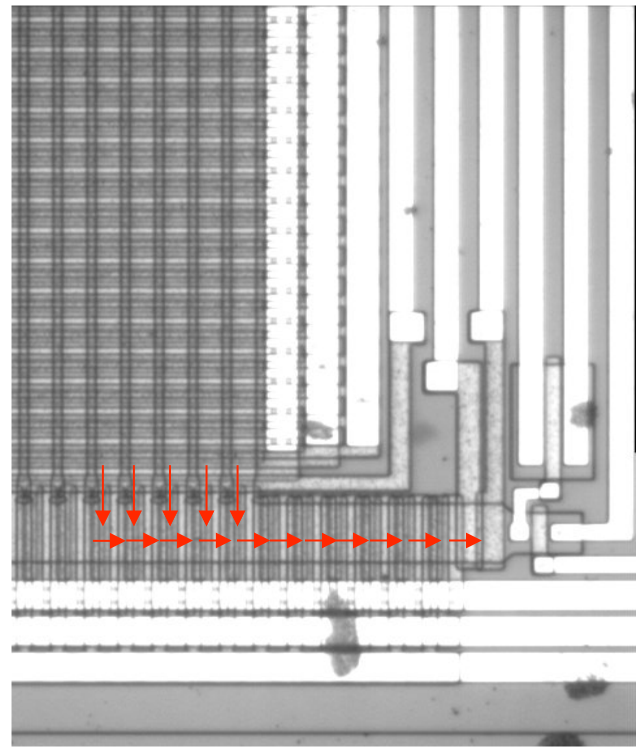


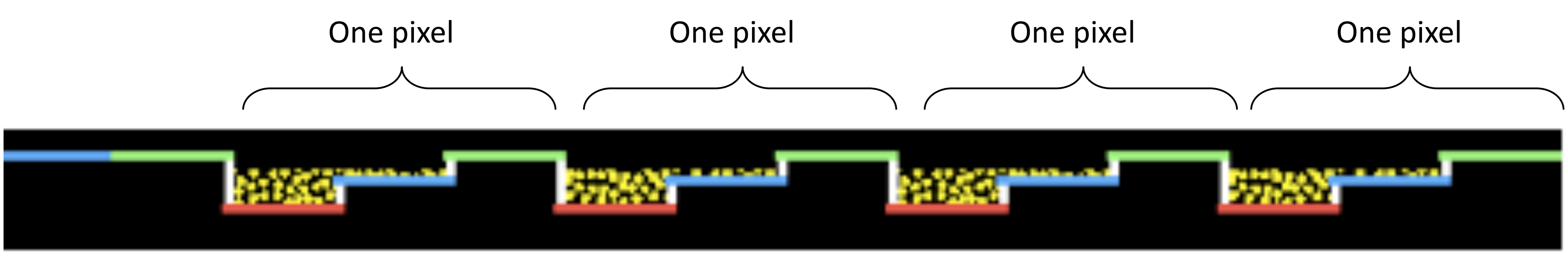




Dark Energy Survey CCD 700x

# Charge collection

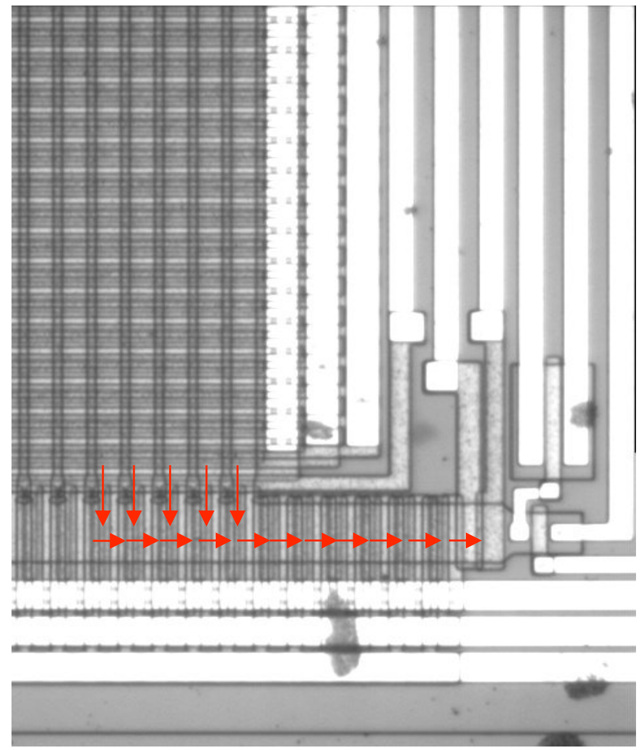
- Example shown is the most common, three phase transfer, which is used for the DES CCDs.
- Each pixel (MOS capacitor) has 3 gates (electrodes)
- During integration, one (or two) clocks are held low.
- This is where the photo-produced electrons will collect.

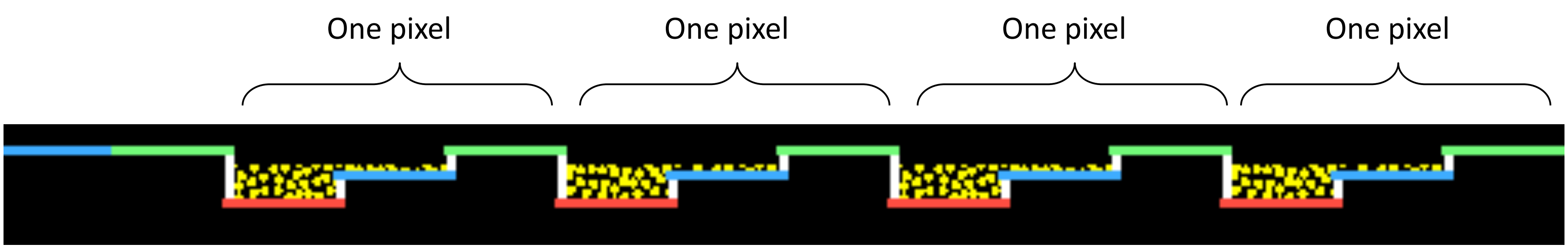




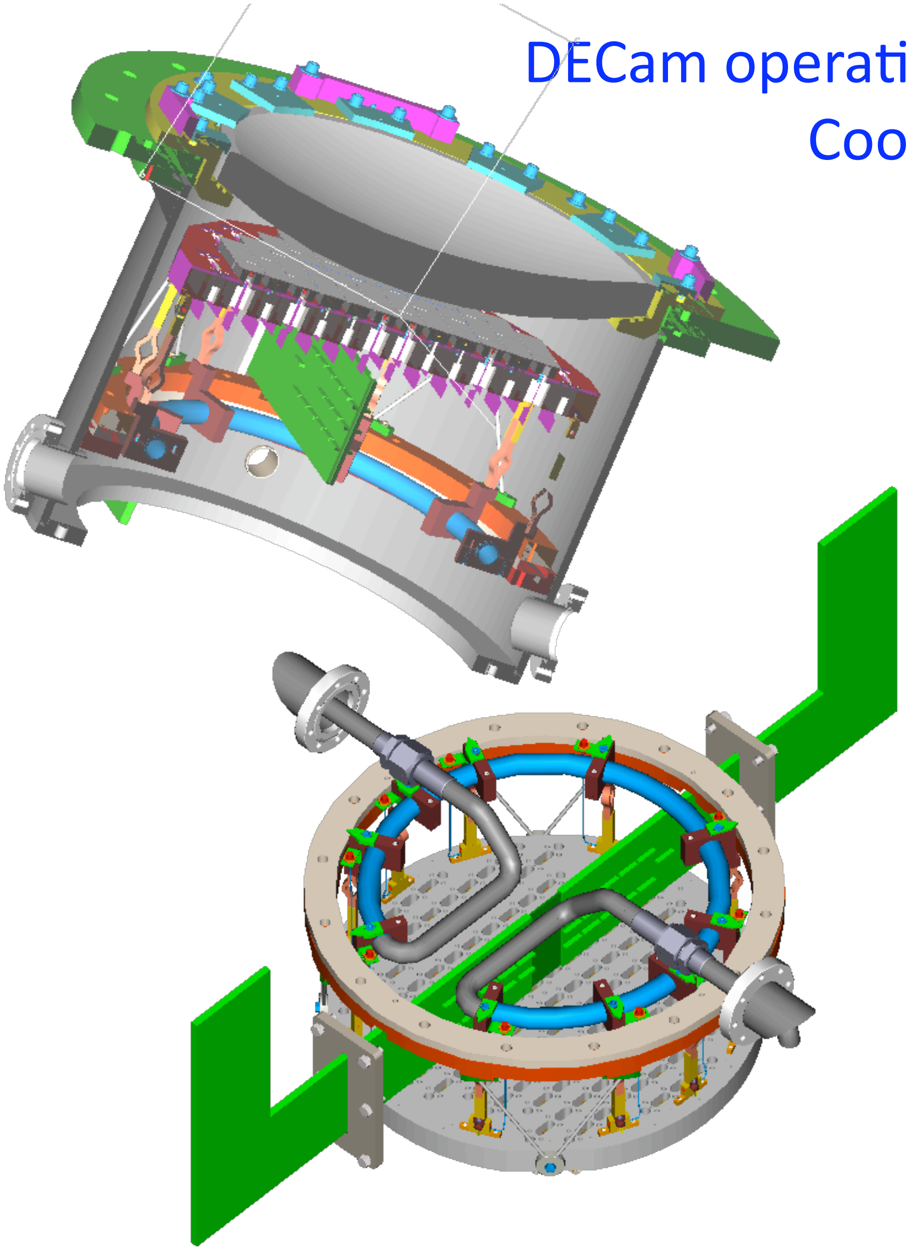
# Charge transfer

- After the integration time has elapsed, the charges are read out.
- Example shown is the most common, three phase transfer, which is used for the DES CCDs.



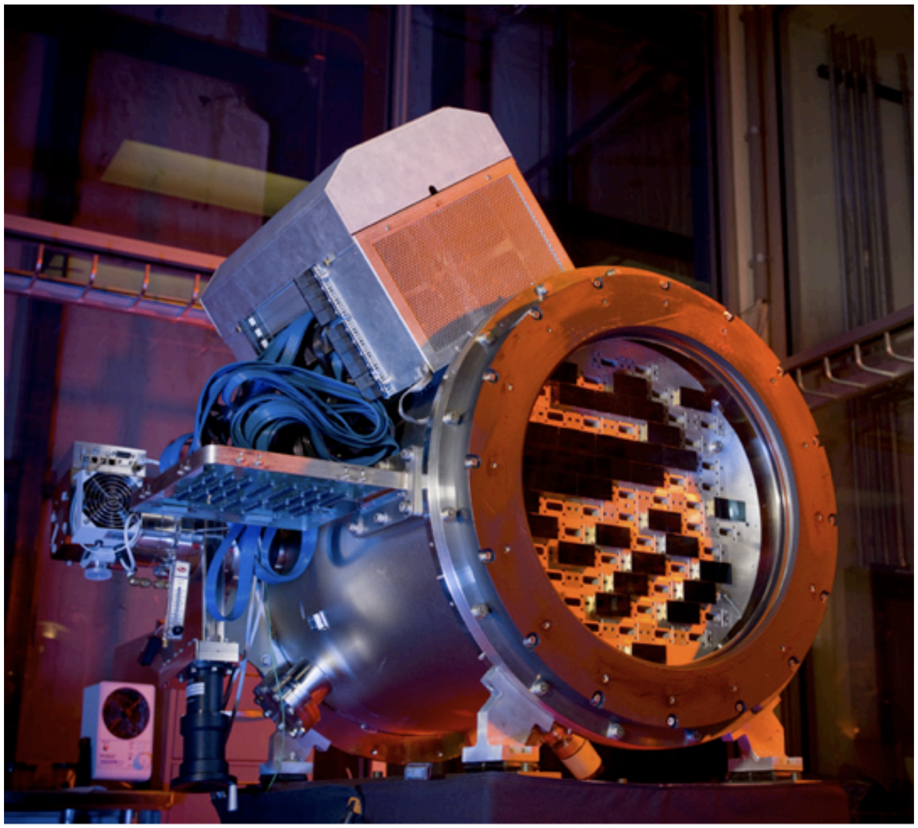


# DECam operating parameters
# Cooling



- DECam will operate at −100 degrees C
- ~1 W / CCD
  - ~1/3 W electrical (amplifiers)
  - ~1/6 W heat conduction from wiring
  - ~1/2 W radiation
- Cooled with liquid nitrogen

# DECam operating parameters
# Vacuum



- Operate at ~ 1E-6 Torr with ion pumping
  - Need to prevent condensation on surface of the CCDs.
  - The required pressure is a function of operating temperature, because the vapor pressure of water is a function of temperature.
  - When cold, the vacuum is even better due to cryo pumping.

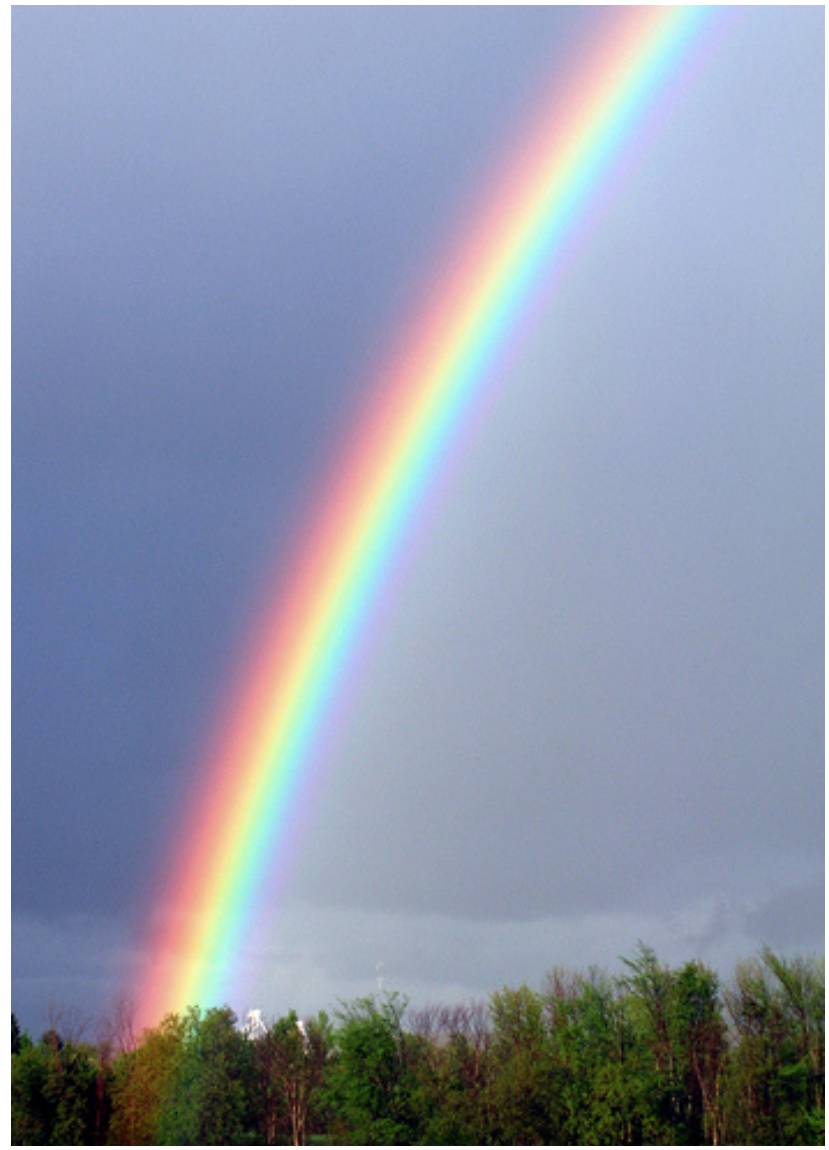
# From Galileo to multiwavelength observations

- Galileo's observations only show us what things look like in the optical part of the spectrum: the light that the human eye can detect.

Hubble Ultra Deep Field

# Rainbows

- But look at a rainbow…
- Each color transitions to the next, but when you get to either the red or the violet end, the rainbow seems to stop, or fade into nothing.
- Or does it just actually transition to colors that are invisible to our eyes?



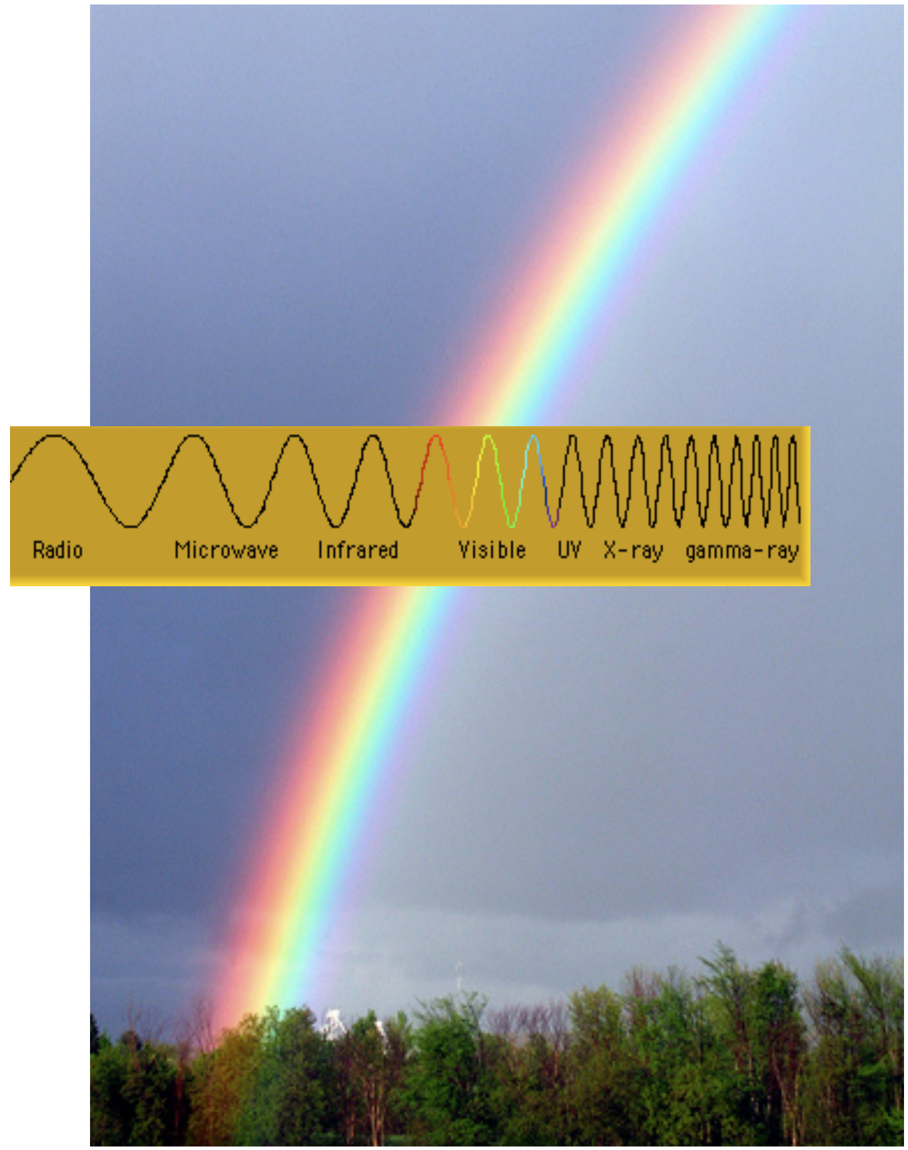
# Rainbows

- If we put other detectors on either side of the rainbow, could we detect more ‘colors’?

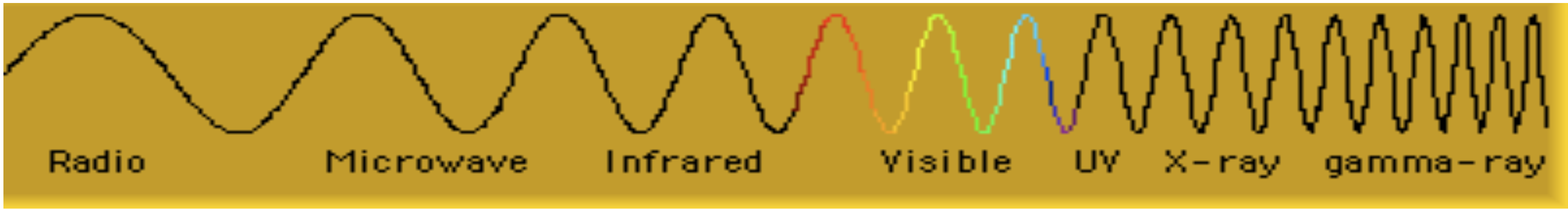
- Yes.

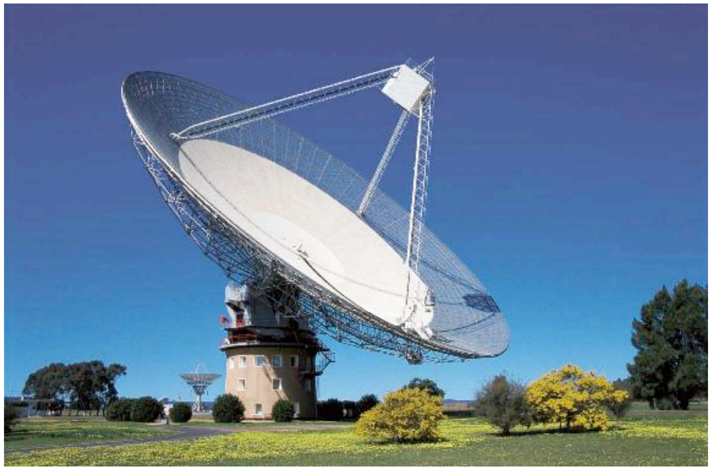
# Wavelength

- The different 'colors' have different wavelengths.

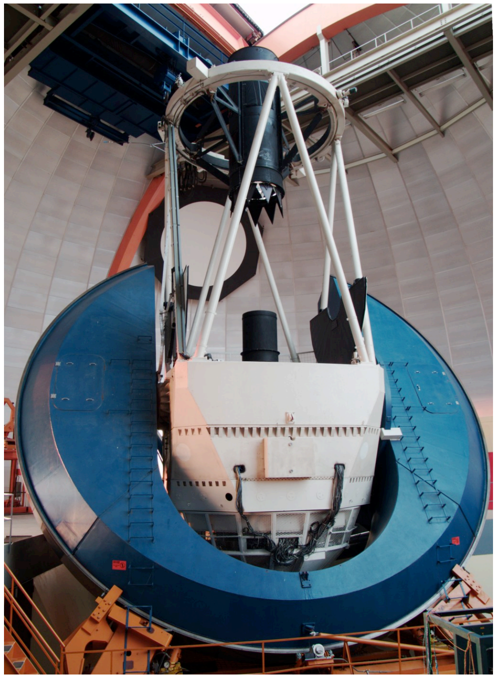


# Different telescopes for different wavelengths



Radio



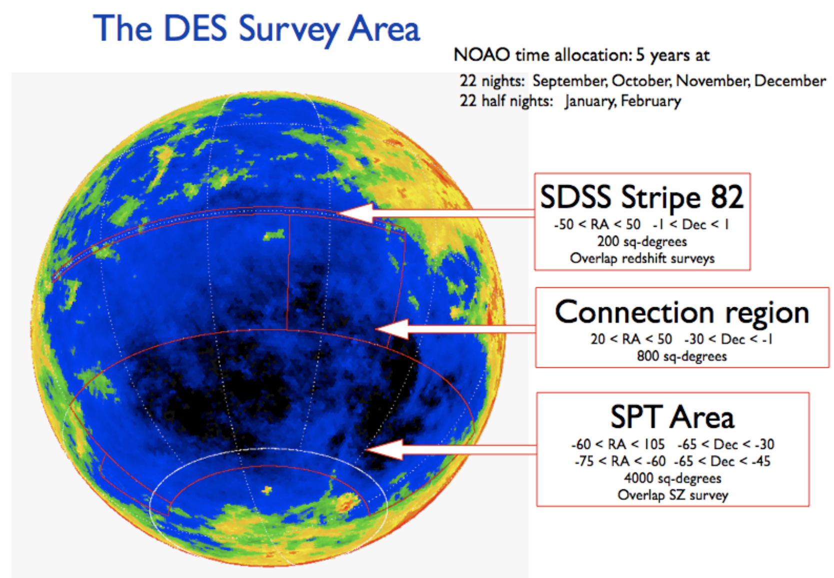
Optical

X-ray

Multiwavelength observations greatly increase our understanding of cosmology

# DES overlap with IR and millimeter wave telescopes

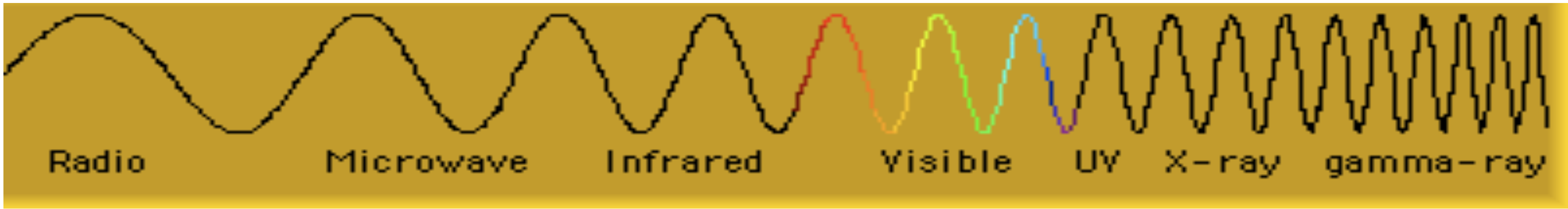
- Overlap with SPT
  - DES will provide SPT with redshifts
  - SPT will provide masses determined via Sunyaev Zeldovich effect (SZ effect)
- Overlap with SDSS Stripe 82
  - Provides calibration of DES photometric redshifts with SDSS spectroscopic redshifts
- Overlap with VISTA
  - DES will provide Y band to VISTA
  - VISTA will provide DES with near infrared data (improves DES photo-z)





South Pole Teleccope

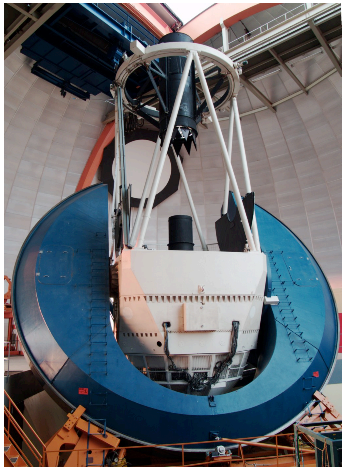
# Different telescopes for different wavelengths





SPT
Millimeter wave

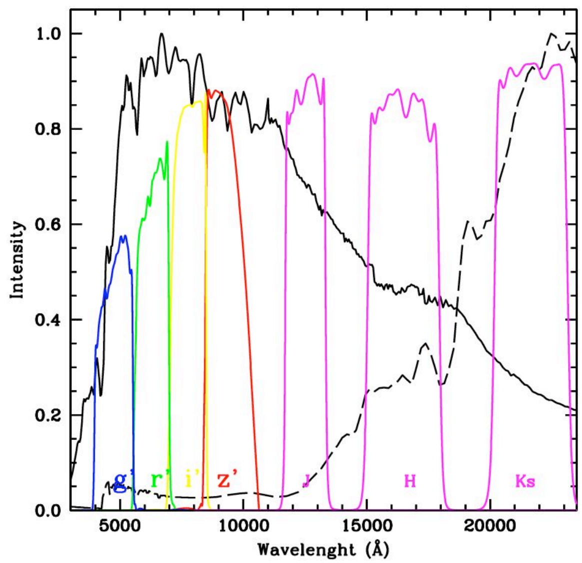
VISTA
Infrared



Blanco
Visible, near-IR

# Visible and Infrared Survey Telescope for Astronomy (VISTA)

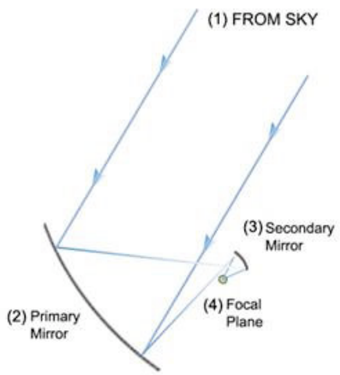
- VISTA is a 4-m class wide field survey telescope for the southern hemisphere, equipped with a near infrared camera (HgCdTe) and available broad band filters at Z,Y,J,H,$K_s$ and a narrow band filter at 1.18 micron.




VISTA
Cerro Paranal Observatory

# South Pole Telescope (SPT)

- The South Pole Telescope is designed to measure the properties of the Cosmic Microwave Background (CMB)
- Most of this light has traveled freely through empty space since its creation, and it arrives at the earth from all directions in the sky.
- Tiny features in these maps will indicate where clusters of galaxies have slightly altered the primordial CMB light, and through studying these clusters we can learn about the evolution of structures in the universe.

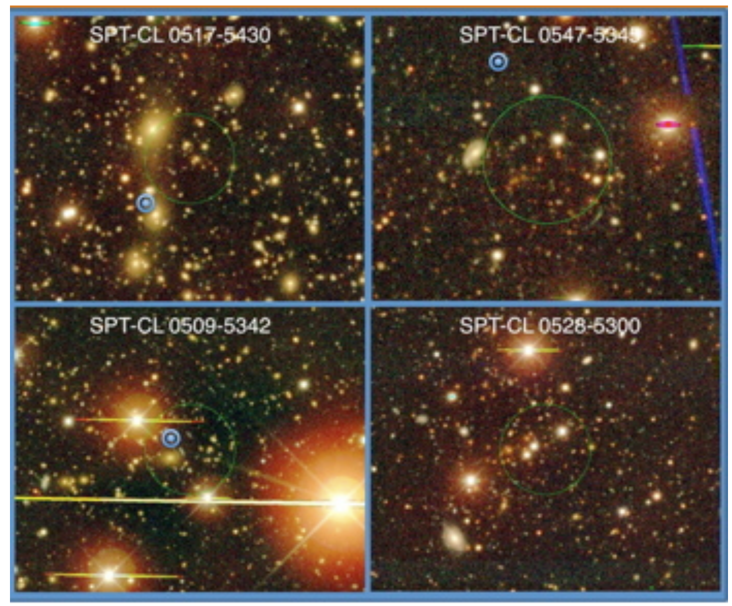



South Pole Telescope

# South Pole Telescope (SPT)

- The SPT can share information about the location and mass of cluster with the DES while DES can provide the SPT with redshift information about the clusters.

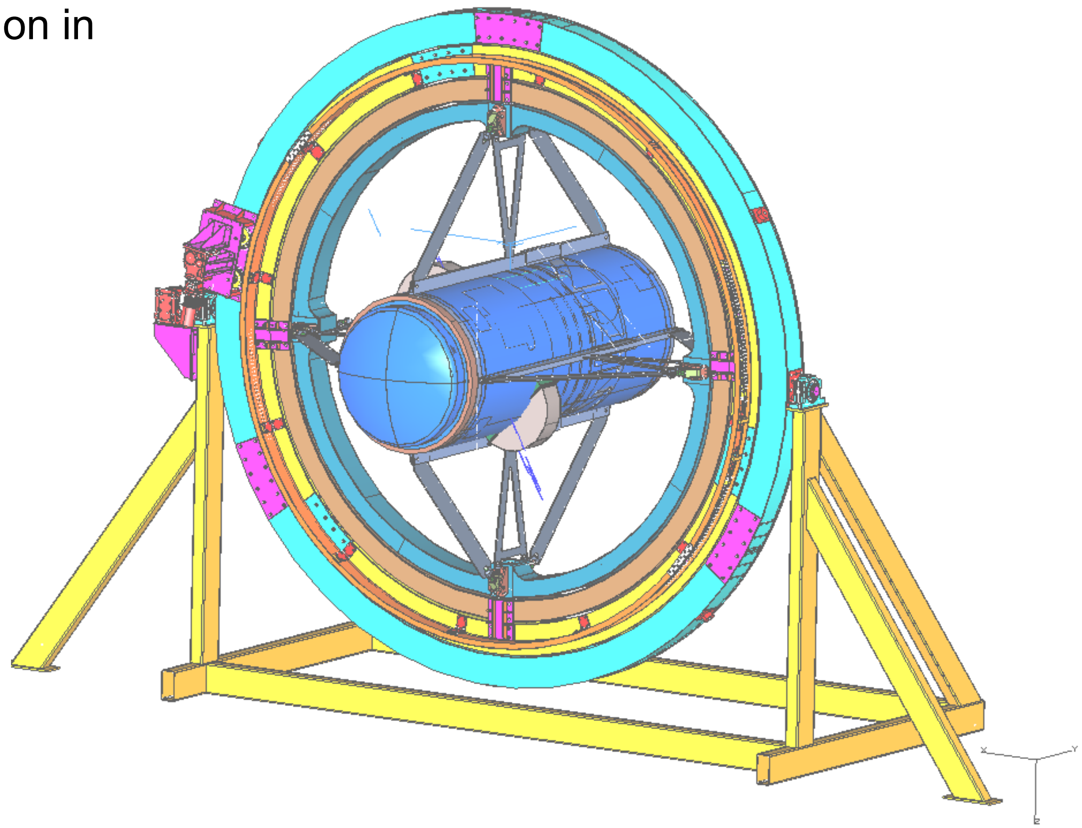
- This information is important, because the rate at which massive clusters form is sensitive to Dark Energy.



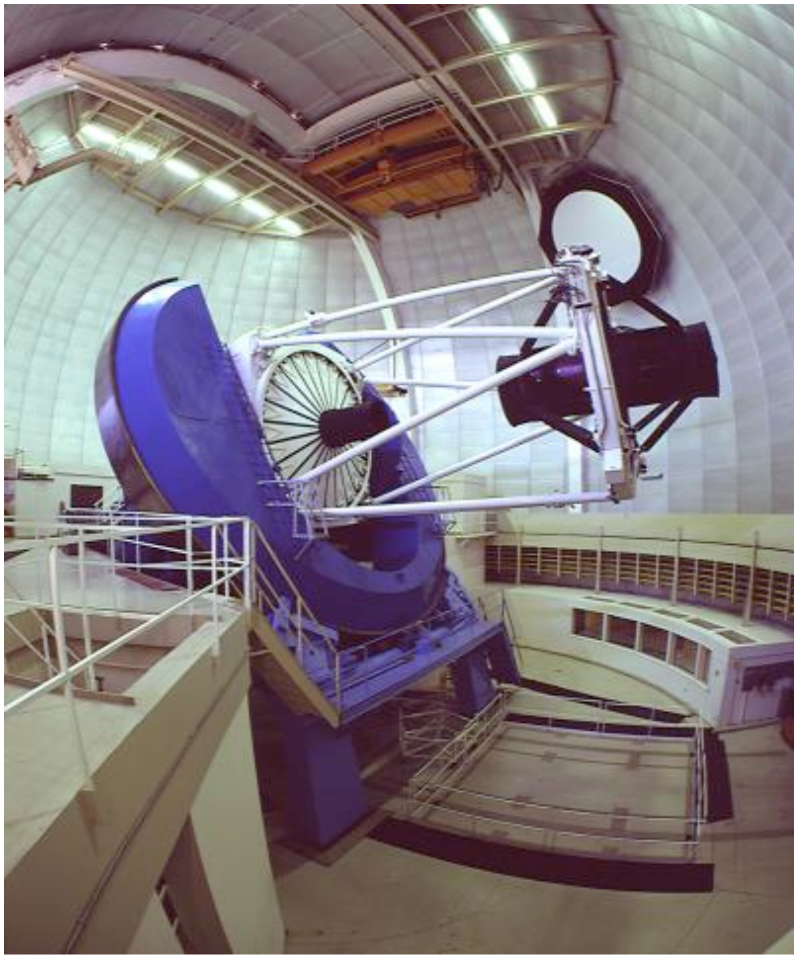

Clusters found using the SPT

# Telescope simulator

- We will place DECam in a specially-built stand to tilt and rotate it.
- This allows verification of operation in all orientations before shipping DECam to Chile.



Goal: Fully commissioned by April 2011



# The best is yet to come!